

*Geology of the Desert Hot Springs - Upper
Coachella Valley area, California*

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CALIFORNIA DIVISION OF MINES AND GEOLOGY

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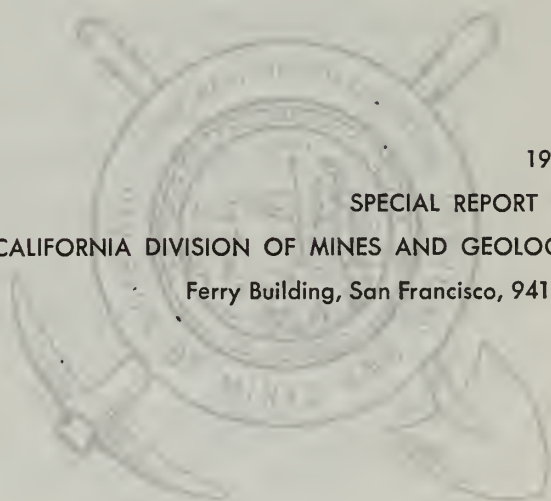
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Geology of the Desert Hot Springs-Upper Coachella Valley area, California

*With a selected bibliography of the Coachella
Valley, Salton Sea, and vicinity*

By RICHARD J. PROCTOR, Geologist
The Metropolitan Water District of
Southern California

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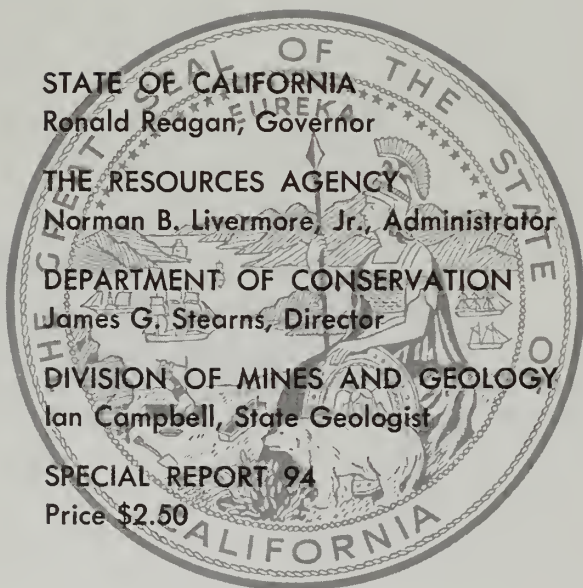
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Frontispiece. Oblique aerial view southeastward across part of the Coachella Valley. The trace of the San Andreas fault is clearly shown by fault-dommed groundwater ollawing vegetation to grow north of the fault. Sand-covered Indio Hills in middle distance; wind-scaured Gornet Hill at right; Little San Bernardino Mountains in background. Community of North Palm Springs in center of photo. Photo by John S. Shelton, 1960.

Geology of the Desert Hot Springs - Upper Coachella Valley Area, California^{*}

By RICHARD J. PROCTOR †

ABSTRACT

The Desert Hot Springs area is in the upper Coachella Valley at the juncture of three natural geomorphic provinces of California—the Transverse Ranges, the Peninsular Ranges, and the Colorado Desert. The mapped area is about 100 miles east of Los Angeles and lies principally in north central Riverside County.

The oldest rocks in the area are Precambrian(?) amphibolitic and migmatized paragneisses of the San Gorgonio igneous-metamorphic (Chuckwalla) complex. They are intruded by Cretaceous diorite porphyry, Cactus Granite, quartz monzonite, intrusive breccia, and basic plutonic rocks. Of probable late Paleozoic age are the metamorphic rocks of the San Jacinto Mountains which form spurs projecting into San Gorgonio Pass and Coachella Valley.

Seven previously named middle to late Cenozoic formations crop out, mainly in the foothills of the San Bernardino Mountains and in the Indio Hills. On the basis of this work, these rocks are believed to represent only four distinct formations, with their outcrop areas separated by as much as 10 miles of Recent sediments. They are the Coachella Fonglomerate/Split Mountain Formation (Late Miocene (?)); the Painted Hill Formation/Canebrake Conglomerate, with interfingering Palm Spring Formation (mid-Pliocene to early Pleistocene); and the Cabezon Fonglomerate/Ocotillo Conglomerate (late Pleistocene).¹ The fossiliferous marine Imperial Formation (early Pliocene) crops out in three widely separated localities, and its relationship to overlying and underlying rock units is a major basis for these correlations.

The Mission Creek and San Andreas (Banning) faults comprise the main tectonic features. The Mission Creek fault shows Recent displacement of 1,100 feet vertically, and 800 feet laterally. Evidence for pre-Quaternary movements is suggested where Miocene basalt and Cretaceous diorite porphyry appear to have been intruded locally into the fault zone. Dips of fault planes within the San Andreas system change markedly from a moderate angle (reverse) in the west of the mapped area, to near-vertical in the east. North-south compression of the Indio Hills has created 12 mappable folds within a 4-square-mile area, all trending subparallel to the San Andreas fault zone. Recent domical warping is expressed in terrace-capped Whitewater Hill.

Observations and collected data indicate little possibility of finding petroleum in the area; mining and quarrying operations are small. The Mission Creek fault has a direct causal relationship to the hot mineral water localized at Desert Hot Springs.

^{*} A condensation and partial revision of a thesis submitted in partial fulfillment of the requirements for the degree of Master of Arts in Geology, University of California, Los Angeles, July 1958. Manuscript submitted to the Division of Mines and Geology for publication September 1958.

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¹ The convention of showing these formations in pairs joined by a slant is followed throughout this report to indicate their believed equivalence.

INTRODUCTION

The Desert Hot Springs area is about 100 miles east of Los Angeles (fig. 1). It includes the upper Coachella Valley (elevation 550 to 2,000 feet); the westernmost Little San Bernardino Mountains (elevations to 3,500 feet in this area); the southern part of Morongo Valley (average elevation 2,700 feet); the foothills of the San Bernardino Mountains; some jutting spurs of the San Jacinto Mountains; and the westernmost 4-mile extension of the Indio Hills. It is the juncture of three geomorphic provinces—the Transverse Ranges north of San Geronio Pass, the Peninsular Ranges south of the Pass, and the Colorado Desert.

The Coachella Valley—pronounced “Co-chella” locally—is the northwest part of the Colorado Desert and merges southeastward into the Imperial Valley. An arbitrary dividing line in wide usage is the northern shore of Salton Sea—thus the Coachella Valley is about 50 miles long and from 10 to 20 miles wide; the area of this report is concerned with the northwesternmost 13 miles of the Valley.

Most of the area is in Riverside County, but the northernmost 7 square miles is in San Bernardino County.

Excellent paved roads traverse most of the mapped area. In addition, there are numerous dirt roads and certain sandy roads to be avoided by ordinary auto-

mobile. The Southern Pacific railroad, Interstate Highway 10, and the Colorado River Aqueduct cross the area.

Geography

Climate

The climate of upper Coachella Valley is classified as tropical desert, with mild winters, very hot summers, and precipitation dominant in the winter months. Summer temperatures commonly exceed 110° F. in daytime but drop to around 75° F. at night; when daytime temperatures exceed 120° F. in the shade, they may reach 180° F. on the exposed ground. In winter the daily temperature range is from the lower 30s to the 80s, and light snow falls every few years on the upper desert floor.

Average annual rainfall in the area is roughly 4 inches on the desert and 15 inches in the nearby mountains. Precipitation varies greatly from year to year. For example, Palm Springs weather station recorded no precipitation in 1896–97, but 10.39 inches for February 1927, and 17.68 for that year. There are no perennial streams on the valley floor; water flowing off the mountains disappears into the sandy alluvium at the foot of the slopes. Although most rain falls between October and April, infrequent flash floods occur in summer. These are so localized that runoff may come rushing out of a single canyon,

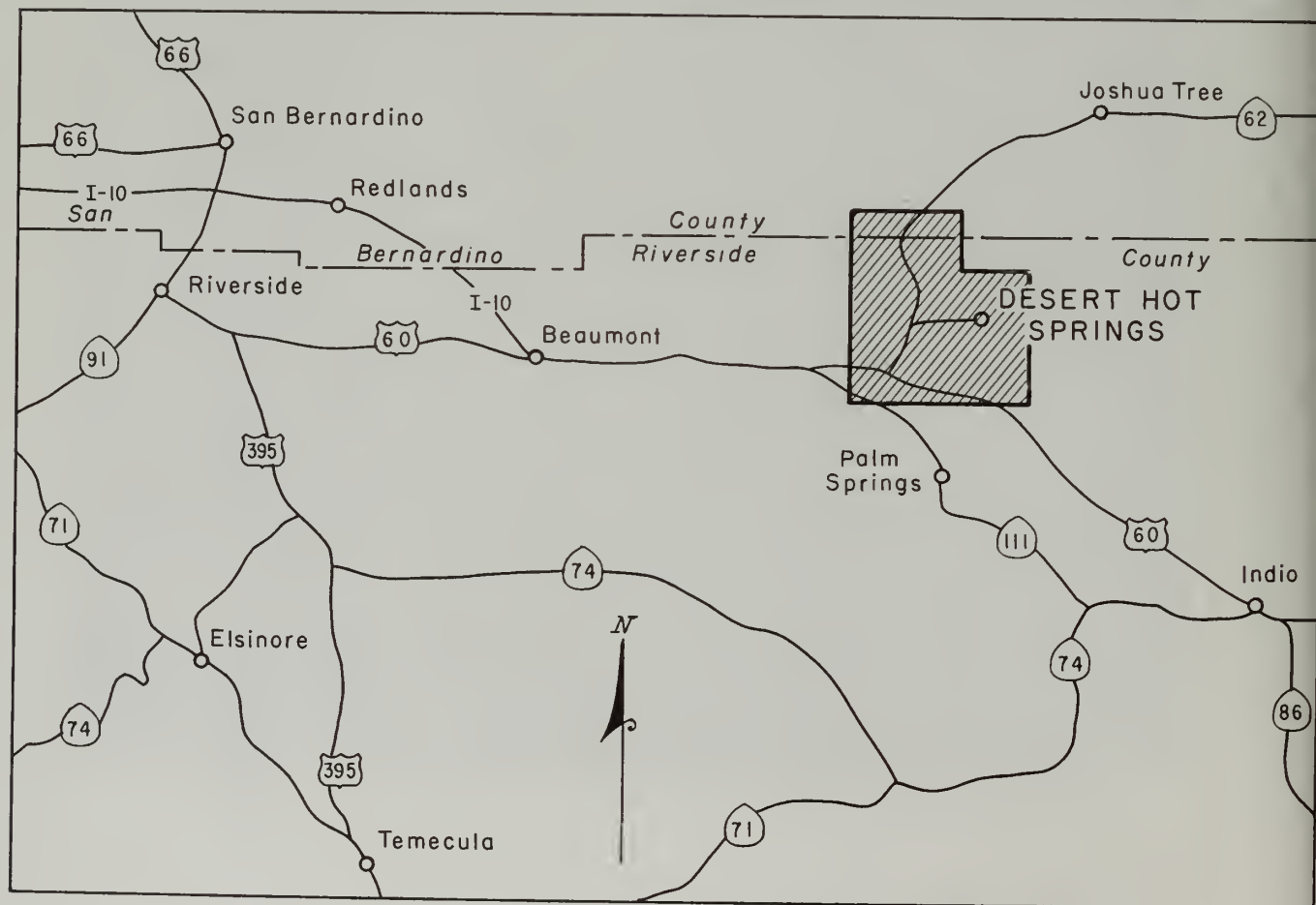


Figure 1. Index map showing location of Desert Hot Springs area.

while those on either side remain dry. Strong west winds blow in the evenings during the summer, and are especially strong in the spring in the southern part of the area.

Vegetation

The vegetation in this area is sparse and is of xerophytic types exclusively. Nevertheless, well over 100 species of plants are indigenous to the upper Colorado Desert (Benson and Darrow, 1954; Jaeger, 1957); a wide variety of them occur in the "Devil's Garden" at the west edge of the map.

The edaphic distribution of soils and flora are little help in distinguishing geologic contacts. Vegetation does help define the traces of the San Andreas and Mission Creek faults on the alluvium where fault-dammed ground-waters migrate upward north of the shatter zones.

At the mouth of San Gorgonio Pass only the sturdiest plants can survive the shearing sandblast effect: some grow only in the lee of wind-scoured boulders where their growth is limited to the outline of the protecting boulder (photo 1).

Among the most common plants in this region are Creosote bush (*Larrea divaricata*); Bigelow cholla (*Opuntia Bigelovii*) or "jumping cactus"; and mesquite (*Prosopis juliflora*) a "water indicator" which defines the trace of the San Andreas fault for some 4 miles west of the Indio Hills, and the Mission Creek fault on the south side of Miracle Hill east of Desert Hot Springs.

Burrowweeds (*Haplopappus*), snakeweeds (*Gutierrezia*), cat claw (*Acacia Gregii*), bur sage (*Franseria dumosa*), and ephedras are all common low brush. Yuccas, agaves (century plant), and juniper (*Juniperus californica*) are especially abundant in Morongo Valley, but the juniper is not found elsewhere in the area. Cottonwood trees (*Populus Fremontii*) are only found in upper, sheltered stream channels such as Mission Creek. The barrel cactus (*Echinocactus acanthodes*) is sometimes interspersed with cholla on remnant patches of conglomerate, especially on Dever's Hill and westward to Devil's Garden. Beginning in the Indio Hills and becoming more abundant eastward is the sinewy, thorny, crimson-tipped ocotillo (*Fouquieria splendens*). America's only native palm (*Washingtonia filifera*) marks the San Andreas fault by several palm oases at the south base of the Indio Hills.

For a few weeks each April, sand verbena and dune and evening primrose color the desert yellow, white, and purple.

Previous geologic work

All previous geologic descriptions of the upper Colorado Desert region are in general terms, with or without reconnaissance maps. Allen (1957) and Dibblee (1954) are the main contributors to the geology of the region as a whole.

William P. Blake (1856) was the first geologist to visit and describe the Colorado Desert; in fact, he named it in 1853—antedating the state of Colorado by 8 years. This first description of the region remains



Photo 1. "Wind-sheared" vegetation. These remarkable pictures show the force of the wind in the pass area. The plants growing on the leeward sides of the boulders have been sandblasted to the exact shape of the scoured rocks that shelter them. These photos were taken atop Windy Point but these features can just as well be seen on the southern side of Garnet Hill, and to a lesser degree, on the western slope of Whitewater Hill.

one of the most complete and eloquent accounts of its physical features.

Charles R. Orcutt (1890) discussed the Colorado Desert in general, emphasizing the vicinity of "Salton Dry Lake", but included no geologic map.

Walter C. Mendenhall (1909) studied the groundwater of the Indio region, and briefly described (p. 11) the rocks at the north side of San Gorgonio Pass. No map was included.

Francis E. Vaughan (1922) mapped 1,200 square miles of the central and eastern San Bernardino Mountains and bordering rugged desert terrain, in 1915, 1916, and 1917.

John S. Brown (1923) briefly explained the geology of the Colorado Desert region, and included reconnaissance geologic map, adapted, in this area, from Vaughan's work.

Brown also discussed Morongo Valley (*in* Thompson, 1929, pp. 638-642), using material from the then unpublished manuscript of Robert T. Hill (1928); this material apparently was deleted from Hill's book before it was printed.

John P. Buwalda and W. Layton Stanton (1930) interpreted geologic events in the history of the Indio Hills and the Salton basin, but did not present a map.

From 1930 to 1933, F. L. Ransome and J. P. Buwalda prepared several geologic reports and maps of proposed aqueduct routes as consultants for the Metropolitan Water District.

Donald M. Fraser (1931) made a geologic map (scale 1 inch equals 2 miles) of the San Jacinto Mountains in a study of the northern Peninsular Range.

Richard Joel Russell (1931) studied the land forms of San Gorgonio Pass.

Wendell P. Woodring (1932) and Richard A. Bramkamp (1934) studied the marine Imperial Formation in this area; Woodring made the most complete collection of Imperial fossils to date. Both included small scale location maps.

In Nelson H. Darton's (1933) guidebook for the Southern Pacific Lines (with maps of scale 1 inch equals 8 miles) the geology in this area is discussed using the material of J. S. Brown and personal communications from L. F. Noble for plotting the faults (Sheet 27), and also using the work of F. E. Vaughan and D. M. Fraser (Sheet 28).

William J. Miller (1944) skirted the lower Coachella Valley in a reconnaissance map (scale 1 inch equals 3 miles) of a strip of land 7 to 22 miles wide from the eastern San Jacinto Mountains to Blythe, on the Colorado River.

T. W. Dibblee, Jr., who has intermittently mapped in the southwestern desert area since 1943, prepared a generalized map of the Imperial Valley Region including a large part of the Coachella Valley (1954). Although the scale of his map (1 inch equals 6 miles) is very small it displays more detail than all other previous works.

Clarence R. Allen (1957) studied the San Andreas fault zone in San Gorgonio Pass. His "Reconnaissance Geologic Map" of the pass has a scale of an inch to the mile, but he includes a large scale (4 inches equal 1 mile) map of the eastern San Bernardino foothills. This has been adapted and only slightly modified in this report.

A detailed seismic study resulting from earthquakes in the Desert Hot Springs area was completed by C. F. Richter, C. R. Allen, and J. M. Nordquist (1958).

Present geologic work

The main purposes of this paper are to describe the geology of the Upper Colorado Desert region, to correlate formations and rock types within this area with those in surrounding areas, to delineate and describe the structures of the San Andreas fault system through the area, and to explain the occurrence of hot natural mineral water at Desert Hot Springs.

The mapped area consists of 125 square miles, 57 of which are not alluviated. Field mapping was done from June 1957 to March 1958. The base map is compiled from the entire 7½' U.S. Geological Survey

Desert Hot Springs quadrangle (1955), the western two-thirds of the 7½' U.S. Geological Survey Sever Palms Valley quadrangle (1958), and the southeastern part of the 15' U.S. Geological Survey Morongo Valley quadrangle (1955). Vertical aerial photographs of the entire area on a scale of 1 inch equals 2,000 feet and several aerial photographs with a scale of 1 inch equals 1,667 feet, were also used.

Acknowledgments. The writer wishes to acknowledge assistance from Professor John C. Crowell, Department of Geology, University of California, Los Angeles and Clifton H. Gray, Jr., of the California Division of Mines and Geology who made helpful observations and read this report critically; Tom W. Dibblee, Jr. of the U.S. Geological Survey, for discussions and field mapping assistance in the Indio Hills and Morongo Valley, which is greatly appreciated; Professor Clarence R. Allen of the California Institute of Technology for discussions, seismic data, and comparison of field data; George Guynes, then an undergraduate student at Redlands University, for discussion and photographs of the San Jacinto Mountains; and Elmer Baddley and Paul Harris of the Texas Company who kindly provided information from their oil well drilled in the Indio Hills in 1954. Thanks are also extended to Engineers Henry J. Mills and Tom J. Cain of the Metropolitan Water District who indirectly made this report possible by giving the author summer employment as Inspector on aqueduct construction in the area.

DESCRIPTIVE GEOLOGY

The oldest rocks in the area are the Precambrian (?) San Gorgonio gneisses. These rocks and the Early Cretaceous (?) igneous rock masses intruded into them, are collectively termed the Chuckwalla complex.

Schists, gneisses, and recrystallized limestone rocks, probably late Paleozoic in age, compose the metamorphic rocks of the San Jacinto Mountains.

All unmetamorphosed sedimentary rocks are late Cenozoic in age, ranging from Late Miocene fanglomerate and basalts to Recent alluvium and sand accumulations. Only the lower Pliocene Imperial Formation is marine; it affords the best clues to the ages of the unconformably underlying Coachella/Split Mountain Formation, and the conformably overlying Palm Spring and Canebrake/Painted Hill Formations. Unconformably above these last-named rock units are the upper Pleistocene Cabezon Fanglomerate/Ocotillo Conglomerate. Figure 2 summarizes the nomenclature and correlation of Cenozoic sedimentary rocks in the Coachella Valley.

San Gorgonio igneous-metamorphic complex (Precambrian?)

Gneiss

The term "San Gorgonio igneous-metamorphic complex" was introduced by Allen (1957, p. 318-319) to include the heterogeneous assemblage of gneisses "of intermediate to basic composition that have been intimately intruded by, and in large part reconstituted by, plutonic rocks of quartz monzonitic composition." The intrusive rocks are dikes, pegmatites, small stocks, and lit-par-lit injections. This complex was first

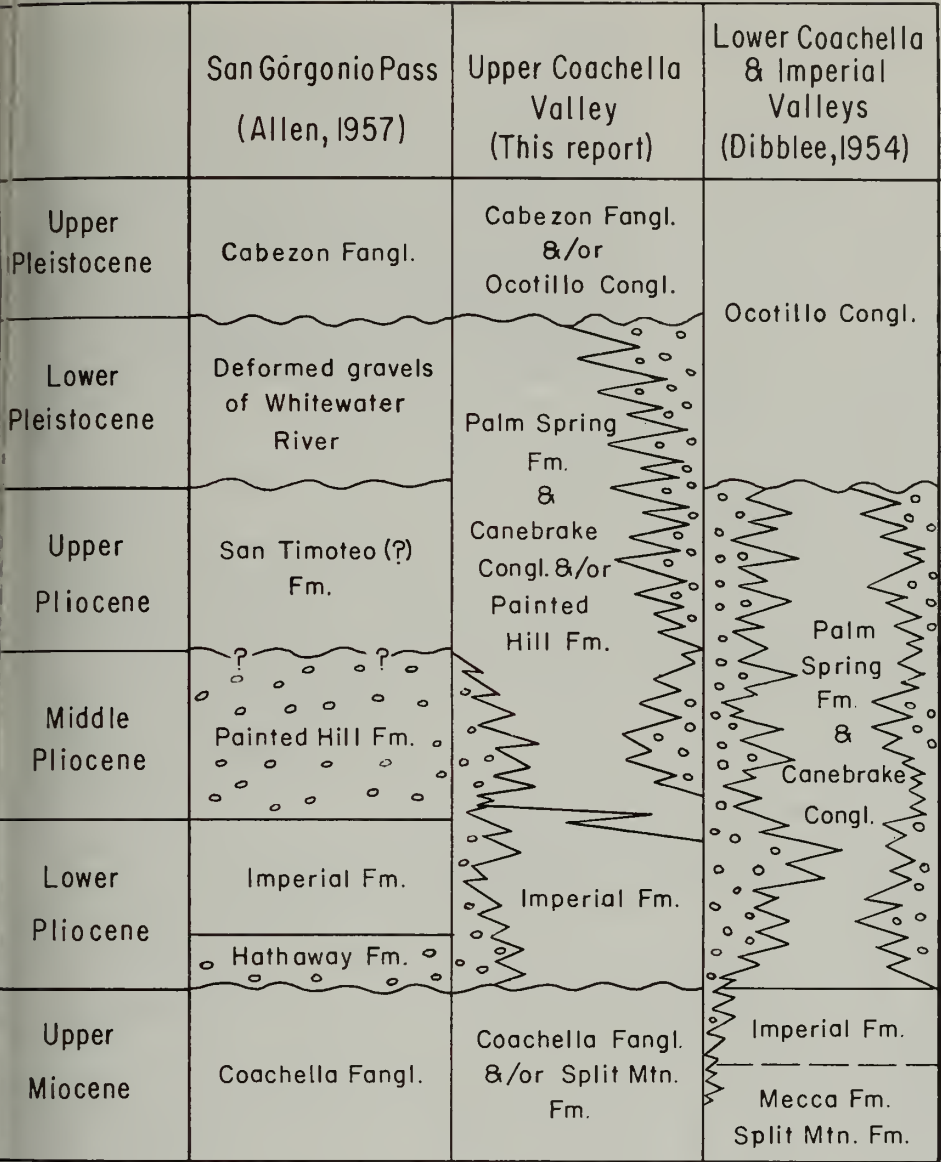


Figure 2. Correlation chart and nomenclature of Cenozoic rocks of the Coachella Valley region. Interfingering of Canebrake Conglomerate from mountains surrounding basin shown diagrammatically, with inferred projection into San Gorgonio Pass. Equivalent rock units indicated by use of "and/or." Only the Imperial Formation is marine.

napped and termed "undifferentiated schists" and "heterogeneous plutonic rocks" by Vaughan (1922). These are also the same rocks which Miller (1944, p. 16-21) named the Chuckwalla complex and which occur in the Little San Bernardino, Cottonwood, Eagle, Chuckwalla, Mule, and Maria Mountains extending 120 miles to the east.

These rocks are exposed in the northern part of the present map in the San Bernardino and Little San Bernardino Mountains, which are arbitrarily separated for purposes of this paper by the Morongo Valley Fault.

Lithology. The gneiss typically is a biotite hornblende quartz andesine-labradorite (An₃₀-An₆₀) gneiss, locally containing small proportions of orthoclase or microcline, and sericite alteration. Epidote or chlorite locally stains the gneiss green, as does the uncommon saussuritization of the pale layers. Sphene, apatite, garnet, and magnetite are also present. These rocks, as a whole, correspond to a range of metamorphic facies

including the greenschist, albite-epidote-amphibolite, and the lower grade amphibolite facies of Williams, Turner, and Gilbert (1955, p. 172). The deliberately



Photo 2. Typical exposure of San Gorgonio gneiss. Thin crenulated layers of intermediate to basic paragneiss composition, very rich in biotite. Numerous thin stringers of aplite concordantly cut the strata.

AGE	FORMATION	SYMBOL & THICKNESS	
Recent	Sand and alluvium	Qs & Qal	
	Terrace deposits	Qt <30'	
Pleist.	Cabezon Conglomerate and/or Ocotillo Conglomerate: Sandy, ill-sorted debris: ss= resistant sandstone.	Qc >1500' Qo >2400'	ss
	Painted Hill Formation and/or Canebrake Conglomerate: Coarse, bouldery debris; b = basalt flow cg= resistant conglomerate bed	Tph >3400'	b cg
Middle & Upper Pliocene	Palm Spring Formation: Equus cf. (Plesippus) & brackish water fossils found near top of beds.	Tc >2000' Tps	
Lower Pliocene	Imperial Formation: Near shore marine, fossiliferous sandy siltstone; 2 foot thick tuff bed on Garnet Hill.	Ti Painted Hill 0-100' Ti Garnet Hill >70' Ti Indio Hills, 0-1660'	
Upper Miocene	Coachella Conglomerate: Red-brown well indurated conglomerate and sandstone; Tcb= olivine basalt flows.	Tc >4600'	
	Split Mountain Formation (Not exposed on surface)	Ts Tcb 300'	
Cretac.	Cactus Granite and quartz monzonite diorite porphyry —contact not exposed—	c qm di	
Late Paleozoic	Metamorphic Rocks of the San Jacinto Mountains: Quartzite-mica-schists, recrystallized limestone and gneisses. —contact not exposed—	ls m >10,000'	
pre-E(?)	San Gorgonio Complex (Chuckwalla Complex): Amphibolite and migmatitic paragneisses.	sg >20,000'	

Figure 3. Columnar chart of Desert Hot Springs area.

unspecific terms amphibolite and migmatitic gneiss probably best describe these rocks.

The gneiss appears to consist chiefly of thin rude bedding planes of alternating pale and dark layers (paragneiss) ranging in thickness from a fraction of a millimeter to several feet, with the pale layers being thicker. The boundaries between layers are commonly sharp, revealing metasedimentary bedding planes shown as foliation attitudes on plate 1. Commonly the appearance changes abruptly to reflect various degrees of injection, including migmatitic and lit-par-lit, as in photo 3. Small, poorly defined segregations and

gradationally bounded basic plutons are very common but they were not mapped in detail.

The lepidoblastic texture of the dark layers is dominated by biotite flakes, some as large as 3 mm in diameter, but mostly as minute specks which cleave with the bedding. The hornblende crystals are variously oriented, but commonly their c-axes lie parallel to foliation.

The pale layers are generally coarser grained, with crystalloblastic textures; they are white to gray, infrequently stained pink by secondary hematite in fractures and small joints. Most of these layers are con-



Photo 3. Gneiss contorted by minor xenolith-rich injections. Both photos taken in Blind Canyon north of Desert Hot Springs. These sudden changes in texture are a common aspect of gneisses in the Little San Bernardino Mountains. (Width of outcrop shown in photo about 5 ft.)

concordant metasediments, but an occasional one branches with poorly defined boundaries through overlying layers, as a penecontemporaneous injection. In addition to their being cut by later (Mesozoic) injections, the gneisses apparently were "granitized" under regional metamorphic conditions, during which the pale layers flowed more readily than the dark layers, perhaps owing to lower melting points of the light-colored minerals.

The original sediments, probably psammitic and pelitic, apparently were altered to their present metamorphic equivalents with the help of "soupy" igneous injections. Foliation attitudes are very inconsistent owing to extreme contorting of the ancient sediments, as well as disruptive effects of later granitic intrusions of at least two stages; on the geologic map, they are rounded off to the nearest 5° or 10° . Clasts of porphyroblastic garnet-sillimanite schist were found in terrace deposits in the area. These rocks, of extreme dynamothermal facies of metamorphism, apparently represent deeper burial and higher confining pressures during recrystallization than any of the gneisses mapped in place in this area. A body of this rock several hundred feet long occurs in the northeastern part of the Little San Bernardino Mountains, $2\frac{1}{2}$ miles east of the mapped area.

The gneiss at Painted Hill, which has been hydrothermally altered to a red and yellow hematite-stained mica schist containing occasional porphyroblasts of tourmaline, is sold as "Whitewater stone" (see Economic Geology section).

Calcareous sediments were mapped only in three small concordant lenses in branches of Blind Canyon. The easternmost and westernmost outcrops are coarse-grained (to 12 mm), recrystallized pure white calcite, with minute pink euhedra of brucite, and patches of yellow serpentine. The eastern exposure averages 8 feet thick and about 100 feet long; the western exposure is somewhat larger. The middle outcrop is within an intrusive xenolith breccia and is recrystallized, and strongly contact metamorphosed, corresponding to the pyroxene-hornfels facies of Williams, Turner, and Gilbert (1955, p. 172). The limestone

consists of almost pure pink to gray calcite rhombs, peppered with books of green and brown biotite 1 to 4 mm in diameter. Soft, altered hedenbergite, subhedral dark green diopside, brown garnet, diopside, and some wollastonite occur at the contacts with the gneiss, which is altered locally too.

Thickness. The steeply dipping and rather uniformly striking foliation spanning several miles of the eastern part of the area indicates a thickness of original San Geronio/Chuckwalla sediments estimated by the writer to exceed 20,000 feet.

Age and correlation. The Baldwin Gneiss of Guillou (1953, p. 6) in the San Bernardino Mountains is similar in lithology and degree of metamorphism to the gneiss in this area, as well as in the injection of Cactus granitic rocks. Guillou (1963, p. 7) assigns an early Paleozoic or Precambrian age to the Baldwin Gneiss, which is overlain by relatively undisturbed pre-Carboniferous quartzites.

Inconclusive evidence points to a Precambrian age for the San Geronio/Chuckwalla complex in this area: the rocks are considerably more contorted than adjacent rocks; no paleontological evidence has been found by investigators throughout its 120 miles of exposures; none of the extensive marine limestone beds which are typical of many Paleozoic sections in southern California were found; and the oldest overlying rocks are Paleozoic.

Cactus Granite and quartz monzonite

Granite and subordinate quartz monzonite both crop out in the mapped area. The name "Cactus granite," introduced by Vaughan (1922, p. 365) and described in detail by Woodford and Harris (1928, p. 271-274), is retained for both rock types. Guillou (1953, p. 12) modified the name to Cactus Quartz Monzonite in the northeastern San Bernardino Mountains, where granite is subordinate to quartz monzonite.

Lithology. Typical samples of Cactus Granite from Little Morongo and Dry Morongo Canyons consist of 30-40 percent milky to yellowish orthoclase, some with a little myrmekitic texture; 15-40 percent partially kaolinized albite-oligoclase (An_{10} - An_{30}); 30 percent clear gray quartz, all with undulatory extinction, and 2-10 percent green or black biotite. Hornblende is not common. Accessory minerals are sphene, zircon, and magnetite, together with some secondary chlorite, kaolinite, and brown iron oxide. Most hand specimens can be crumbled easily in the fingers, and outcrops contain abundant residual arkosic gravels. Sutured contacts between grains of constituent minerals are common. Grains average 2 mm in diameter and are hypautomorphic equigranular, but a few larger phenocrysts of orthoclase give some exposures a porphyritic appearance.

The outcrop of quartz monzonite east of Long Canyon appears quite different from the Cactus Granite just mentioned. It is a dense rock with no sutured grain boundaries; grain size averages only 1 mm; and the orthoclase is pink. Nevertheless, the rock is considered to be a facies of the Cactus Granite inasmuch as Guillou (1953, p. 12) has reported that unit ranges from granite through diorite in composition.

Only in Dry Morongo Canyon, at the northwest corner of the area, is the contact between Cactus Granite and the older gneiss seen to be fairly sharp. Elsewhere, the contact zone includes a gradational gneissoid facies of the granite, in which a zone of typically igneous structures merge into structures characteristic of sedimentary rock. In thin section, primary igneous grains from rocks of this zone exhibit recrystallization rims, which become more abundant with proximity to the contact until the primary igneous texture is replaced by lineated finer-grained gneiss. Apparently, retrograde metamorphism to orthogneiss occurred: first recrystallization occurred along grain boundaries; second, all of the previously existing minerals were assimilated; and finally the light and dark minerals of the granite were segregated into alternate bands.

Dikes. Only the largest aplite and pegmatite dikes of granitic composition were mapped. Typical aplite dikes are xenomorphic granular, pale colored, and associated with larger and presumably deeper intrusions of the underlying Cactus Granite batholith. Of much larger size are the hypautomorphic to pegmatitic textured granite dikes which have as much as 45 percent quartz, and are deficient in accessory minerals and soda-lime feldspars. The largest of these pegmatitic dikes, 30 feet thick, is two miles up Little Morongo Canyon from its mouth.

A 10-foot thick granite pegmatite dike in Blind Canyon, concordant with the gneissic stratification, separates gneiss from younger xenolith breccia. Evidently it was intruded as a last phase in the newly formed contact. Contact metamorphism did not affect the gneiss.

Within the metamorphic rocks of the San Jacinto Mountains, dikes and sills of varying thicknesses are so numerous that only a few are shown (diagrammatically) on the geologic map.

Age and correlation. In the region surrounding the mapped area, the granitic rocks which may be correlative in terms of age and similar magma source are: San Jacinto Granodiorite (named by Miller, 1944, p. 60; described by Fraser, 1931, p. 509-510, as "granite-gneiss and granite"); Bradley Granodiorite (Miller, 1944, p. 52), exposed on the southeastern San Jacinto and northern Santa Rosa Mountains; White Tank Monzonite (Miller, 1938, p. 438-443, and 1944, p. 61-64), which grades from granite to quartz diorite, exposed 10 miles south of Twenty-nine Palms and extensively in the Eagle Mountains; and Fargo Canyon Quartz Diorite (Miller, 1944, p. 59), a 12-square-mile outcrop in the Little San Bernardino Mountains northeast of Indio.

The San Jacinto Granodiorite and White Tank Monzonite are considered younger (Cretaceous?) by Miller (1944) than his other granitic rocks (Late Jurassic or older); in particular he correlates the Bradley Granodiorite with the Fargo Canyon Quartz diorite. He does not mention the Cactus Granite.

Most geologists now accept a Cretaceous age for the southern California batholith, which includes the San Jacinto Mountains. Vaughan (1922, p. 374), writes:

"At the close of Jurassic time there was a great invasion of granitic rocks throughout the Sierra Nevada, and these have been traced down in the San Gabriels. It therefore seems fitting to assign the latest granitics of the San Bernardino Mountains . . . to the same age."

Modern age determinations of the granitic rocks of southern California by many workers using potassium-argon decay ratio techniques confirm Vaughan's view that the San Bernardino Mountains granitic rocks (including Cactus Granite) are probably Cretaceous.

Diorite porphyry

The diorite porphyry is best exposed in aqueduct cuts on the ridge between Big Morongo and Midway Canyons, within the Mission Creek fault zone. East of here to White House Canyon, the rocks are crushed and brecciated to a cataclastite. In contrast to Cactus Granite, the diorite porphyry is fresh looking and dense. It consists of black phenocrysts of common hornblende as much as 16 mm in length, randomly oriented within crystals of sodic plagioclase; quartz is rarely observed. The diorite grades randomly into hornblende gabbro in localities where the amphibole is more abundant than plagioclase. The rock is greatly dissected into angular blocks by a myriad of thin shear planes which crisscross the fault zones at various angles. These shear planes range in thickness from a fraction of an inch to 3 inches and are filled with a white clay gouge which is locally stained reddish.

The contact of the diorite porphyry with the gneiss is a transitional zone, generally hundreds of feet wide. The diorite porphyry grades into blastoporphyratic, dark, streaky, granitic gneiss up Big Morongo Canyon, where hornblende is subordinate to biotite and quartz.

Basic plutons

Several basic and ultrabasic plutons and segregations were mapped in the San Geronimo Complex. Each is petrographically different from the other, but in general terms they are medium-grained biotite hornblende gabbros, in some places approaching hornblendite. The masses northeast of Desert Hot Springs are surrounded by haloes, a few inches to several feet thick, which consist of as much as 80 percent clear white quartz, with the remainder sodic plagioclases, and occasional biotite.

Xenolith breccia

A pale aplitic alaskite has partially digested chunks of gneiss in Blind Canyon, creating an intrusive breccia of light green xenoliths.

The inclusions range in size from specks to irregular masses several feet in diameter: they average about 4 inches. Some inclusions have sharp boundaries, displaying idioblasts of hornblende as long as 10 mm; some have reaction rim zoning, with some of the centers showing original foliation. More commonly, the inclusions have gradational boundaries, and the xenoliths appear merely as indistinctly bounded, largely assimilated masses of light-green aphanitic material.

The matrix ranges from pale fine-grained aplite, coarse-grained alaskite consisting of quartz, orthoclase, and albite. The only accessory minerals are minor amounts of penninite-chloritized biotite. Grossular garnet, dark-green diopside, grass-green vesuvianite, and epidote occur where the limestone lens shown on the geologic map has been contact metamorphosed to a hornfels. These metamorphic minerals are commonly a few millimeters to 1 inch in length, but one thoroughly brecciated orange-brown garnet crystal was 5 inches in diameter. Fractures throughout the intrusive body contain gypsum, and dendrites of manganese dioxide.

Metamorphic rocks of the San Jacinto Mountains (late Paleozoic)

Interbedded mica schists, recrystallized limestones, and granite gneisses occur as roof pendants, inclusions, and tilted strata surrounding the San Jacinto Mountain block. The rocks were described in detail by Fraser (1931, p. 504-508) and Miller (1944, p. 21-25).

These rocks were called a "metamorphic series" by Fraser (1931, p. 504) and the "Palm Canyon Complex" by Miller (1944, p. 21), who includes two stages of younger igneous intrusions. Vaughan (1922), the first geologist to map these rocks, includes them in his Cactus Granite. Allen (1957, p. 322) terms them "Crystalline Rocks of the San Jacinto Mountains" and bases his comments on the observations of these previous investigators.

In this paper they are called "the metamorphic rocks of the San Jacinto Mountains".

Lithology. The metamorphic rocks of the San Jacinto Mountains (photo 4), as typically exposed on the ridge that terminates at Windy Point, consist of rather uniformly banded, crenulated, and locally migmatized schists and gneisses. These rocks are believed to be derived from ancient marine sediments that were dynamothermally metamorphosed and later injected by at least three sets of granitic dikes and sills. The rocks at Windy Point are greatly fractured but no definite fault could be found. Mica schist is the most abundant rock type, recrystallized limestone second, and granitic gneiss third.

The mica schist consists of muscovite, biotite, sodic feldspars, and quartz—in places quartz is abundant enough to form quartzite. Garnet can occasionally be discerned. The beds are platy, tan to dark brown and gray, and with occasional exceptions, fine grained. Biotite, and lesser amounts of muscovite, mark thin, rude bedding planes of the original argillaceous sandstones and impure shales and form the planes of schistosity. These rocks apparently have been granitized, in part by lit-par-lit injections, and in part by sills, dikes, and thin stringers of pegmatite, aplite, and silicite.

The beds of recrystallized limestone range in thickness from a knife edge to intermixtures with the schist hundreds of feet thick. The texture is fine to coarse grained, with some calcite crystals 20 mm in length. The beds are white, blue-gray, and brown; some, where graphite predominates, are black. The graphite occurs in small nodules about 1 mm in diameter, and probably represents altered organic inclusions. Many

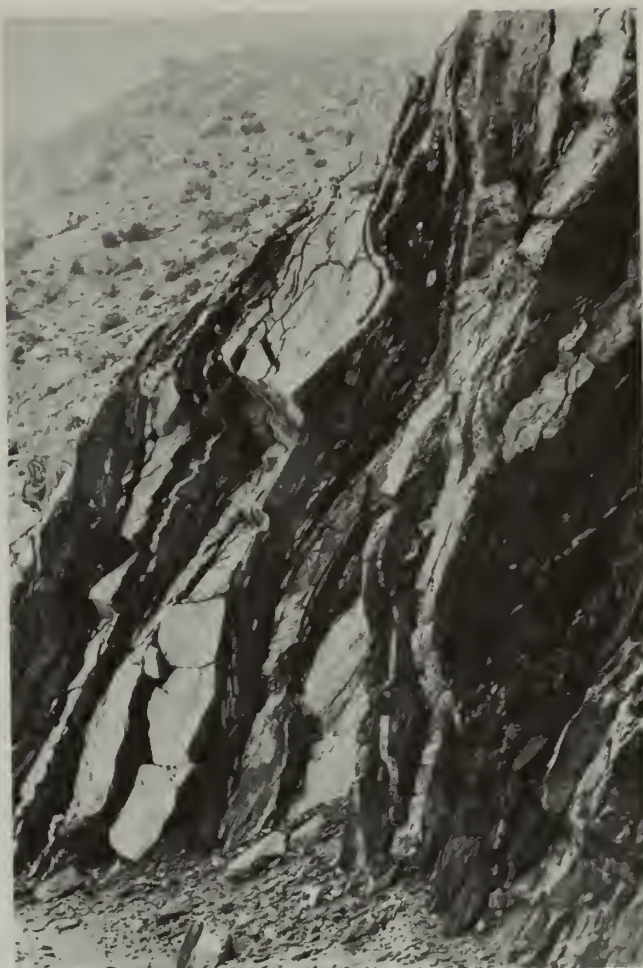


Photo 4. Typical exposure of metamorphic rocks of the San Jacinto Mountains. Granite pegmatite and aplite dikes semiconcordantly cutting mica schist (dark rocks). Thicker beds of recrystallized limestone at left. Strata here dip 75° to the northeast; the strikes of the San Jacinto metamorphic rocks in the area are uniformly northwest. (Height of foreground about 8 feet.)

beds are pure calcite and large enough to be of economic importance (see section on economic geology), but more commonly they are granitized and silicified, and include grains of quartz, epidote, garnet, and biotite, as well as small granitic schlieren and angular xenoliths.

In some joints and caves, redeposited calcium carbonate has formed smooth surfaces. A few solution caves exist. Solution and running water have formed a canyon 300 feet long, 20 feet wide, and 30 feet deep in a former joint in the marble, south of Windy Point. Most joints in this area strike about N. 50° W., and dip 50° to 80° north, almost perpendicular to the bedding.

The granitic gneiss apparently was originally injected into the schists and limestones as sills and semiconcordant dikes prior to dynamothermal metamorphism. These sills and dikes were cut in turn by another pre-metamorphic dike complex, and by dikes associated with the Cretaceous batholithic intrusion. The dominant rock type is a biotite-rich meta-diorite

gneiss which grades into the mica schist, and forms a biotite feldspathic schist which totally obliterates the original rock at the contact. Xenoliths of country rock are common in the gneiss.

Thickness. Fraser (1931, p. 507) estimated the total thickness of the metamorphic rock of the San Jacinto Mountains at about 8,000 feet. Aerial photos of the Windy Point area show a 2-mile thickness of uniformly striking metamorphic rocks that dip northeast 38° to near vertical. Roughly measured, these rocks are more than 10,000 feet thick.

Age and correlation. No fossils were found by the writer in the course of this study. The thorough recrystallization of the limestone strata apparently has helped obliterate the fossil record. However, Webb (1939) found a Mississippian coral (cyathophylloid) in a western extension of the San Jacinto block near Hemet, and Miller (1944) recovered possible crinoidal fragments near Cathedral City, 6 miles south of the area of this report, which he concluded were probably Paleozoic. Fraser (1931, p. 508) simply states these rocks are probably Paleozoic or older, chiefly on the basis of Vaughan's work (1922). John C. Hazzard, who has worked extensively in Paleozoic and Precambrian sections in southern California, believes (personal communication, 1957) the metamorphic rocks of the San Jacinto Mountains may even be early Mesozoic.

Following Fraser's statement, and compatible evidence in nearby areas, the writer believes the metamorphic rocks of the San Jacinto Mountains to be probably late Paleozoic.

Stratigraphy of sedimentary rocks (late Cenozoic)

Miocene (?) Series

Coachella Fanglomerate

The Coachella Fanglomerate, named by Vaughan (1922, p. 386), is the oldest Tertiary sedimentary unit exposed in the area. Vaughan included in the Coachella Fanglomerate a group of rocks which were first recognized as a distinct younger unit by Brankamp (1934, p. 18) and later described and named the Painted Hill Formation by Allen (1957, p. 328). Where its base is exposed in Whitewater Canyon (its type locality is two miles west of this area), the Coachella Fanglomerate rests depositionally on San Geronio gneiss; it is faulted against hematite-stained schist north of Painted Hill.

Stratigraphy. The Coachella Fanglomerate, described by Vaughan (1922, p. 386-387) and Allen (1957, p. 323-324) consists of east-dipping, ill-sorted debris of angular gneiss, granite and basalt clasts as much as 6 feet in diameter, in a well-indurated coarse arkosic matrix. The basalt fragments are especially abundant in the extreme southern and northern exposures of the fanglomerate—about 6 square miles including the area adjacent to the west edge of the geologic map. The unit becomes less consolidated towards the top of the section, with a decrease of marker beds of gray arkosic sandstone, conglomerate, and mauve volcanic debris.

Total thickness of the Coachella Fanglomerate measured from its base in Whitewater Canyon to the first

canyon south of Mission Creek, was estimated to be 4,600 feet.

A series of basalt flows as much as 300 feet thick occurs 850 feet above the base of the unit. These flows also lie upon gneiss in Mission Creek Canyon and are overlain in places by Cabezon Fanglomerate (upper Pleistocene). These flows, in part flow-breccia, are chiefly aphanitic olivine basalt, with minute laths of labradorite. The flows are commonly weathered, disintegrated, and stained a characteristic reddish purple.

By their nature, fanglomerates must be deposited near the base of a mountain mass. The over-steepened 20° - 40° easterly dip of the Coachella Fanglomerate strata, and currently active faults at the base of the San Bernardino Mountains, indicate that they were rising while the fanglomerate was being deposited, and have since continued to rise.

Age and correlation. Although no fossils have been found, the fact that the Coachella Fanglomerate lies unconformably beneath the lower Pliocene Imperial Formation (structure section B-B'), means it is at least lower Pliocene. A Miocene or older age seems likely, to allow enough time for the sediments to accumulate.

The Split Mountain Formation, named by Tarbet (1944, p. 1781) and described by Dibblee (1954, p. 22, 23), is not exposed in this area but is encountered at depth in the Indio Hills (structure section E-E'). Here, the core of The Texas Company "Edom" well bottomed (total depth 7,468 feet) in a fossil-barren red-brown conglomeratic sandstone identified by company geologists as Split Mountain Formation, 2,070 feet beneath the Pliocene marine Imperial Formation.

Although outcrops of the Coachella Fanglomerate are separated from those of the Split Mountain Formation west of the Salton Sea by many miles of alluvium, both were deposited as fanglomerate in the same extended trough of the present Colorado Desert. Also, both are associated with volcanic flows—the Alverson basic andesite, 400 to 700 feet thick, overlies the Split Mountain Formation—which were laid both on "basement" rocks and on fanglomerate. Tom Dibblee also (personal communication, 1957) believes that they may be correlative.

That the Mecca Formation, essentially a fanglomerate that grades into sandstone, may also be correlative with the Split Mountain Formation is suggested by Dibblee (1954, p. 24).

The conclusion here submitted is that the Coachella Fanglomerate and Split Mountain Formation are correlative in that they were (1) created by similar provenance—sediments at the base of low mountains enclosing a trough; (2) similar associated (Miocene?) volcanic activity; (3) similar lithology—nonmarine "basement" debris with sandstones; (4) similar age—probably late Miocene; (5) similar position in the stratigraphic column—they are the oldest late Tertiary nonmarine sediments bordering the Colorado Desert, and both are overlain by the Imperial Formation.

It is best that the existing nomenclature should be retained, in that these areas are widely separated in the trough and deposition was not uniform throughout, giving rise to local names. Also, newer evidence may tend to discredit such a broad correlation.

iocene Series

Imperial Formation

The marine Imperial Formation, named by Woodring (1932, p. 7), crops out in three widely separated areas as shown on the geologic map: the Indio Hills, Garnet Hill, and east of Painted Hill. In 1922, Vaughan (p. 375) described a marine bed exactly 7 miles west of the occurrence of Painted Hill but on the south side of the San Andreas fault (Fig. 4). He called this the "Lion sandstone" after Lion Canyon north of the town of Cabazon. More detailed work by Allen (1957, p. 13) shows this to be the Imperial Formation, and marks its westernmost occurrence. The foothills of the Signal Mountains just south of the Mexican border are the southern and easternmost occurrences. North of the type locality—the south side of Carrizo Valley—the Imperial Formation attains its maximum thickness of 3,900 feet (Dibblee, 1954, p. 22).

The paleontology of the northernmost exposures of the Imperial Formation was studied in detail by Bramkamp (1934). Numerous other studies have been made, which are discussed by Durham (1950).

Indio Hills exposure. In the northwestern Indio Hills only the uppermost part of the Imperial Formation is exposed, in small gullies on the south side of a

ridge. Elsewhere it is buried by a thick mantle of Ocotillo Conglomerate and shifting blowsand. The conformably overlying Palm Spring Formation and Canebrake Conglomerate apparently have been eroded away at this outcrop. The Imperial beds stand out in contrast to the surrounding debris by their yellowish-gray color, fissile claystone lithology, and abundant clusters of gypsum crystals several inches in diameter.

Fresh exposures show gray-brown fissile claystone which weathers to a yellow, iron oxide (jarosite?) stained rubble of small friable chips. Siltstone and fine-grained sandstone crop out locally, and where cemented by secondary calcium carbonate, form resistant lamination planes and lenses.

The data for structure section E-E' north of the San Andreas fault are extrapolated from surface evidence and data given the writer by The Texas Company, from their "Edom" well drilled on the anticline south of the San Andreas fault. The Imperial section of 1,660 feet here is the thickest yet reported outside of the Imperial Valley. The tight folding near the "Edom" well is believed to extend into the incompetent Imperial beds, rather than exist as superficial folds representing adjustments between the two major faults. Indeed, the whole Indio Hills represents a "large anti-

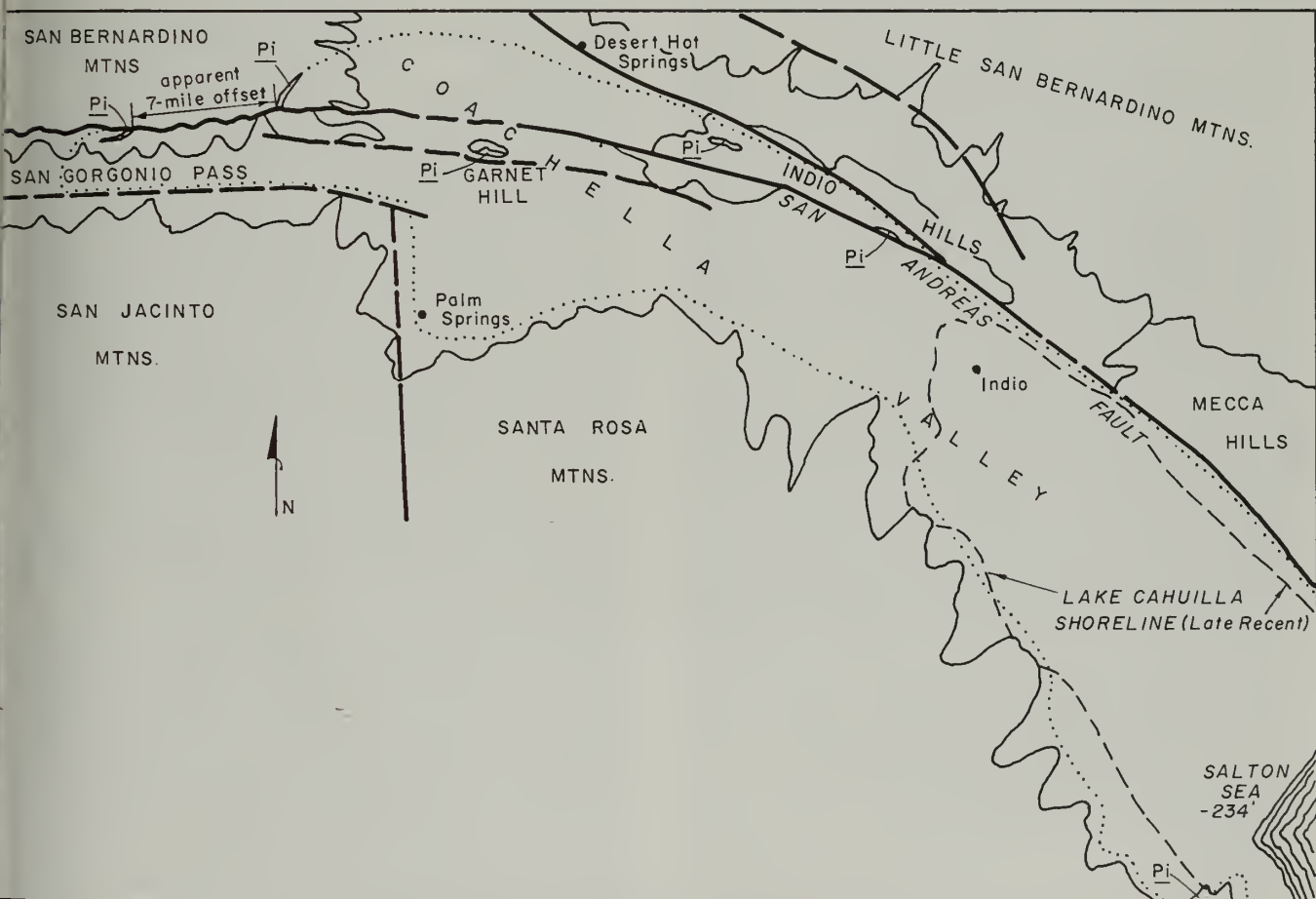


Figure 4. Sketch map showing the six Imperial Formation (Pi) outcrops in the Coachella Valley. Dotted line represents possible subsurface extent of Imperial Formation, as may be encountered in cores. Lake Cahulla shoreline dashed. Present maximum elevation of Imperial beds in San Gorgonio Pass is 2500 feet above sea level, indicating that much uplift since mid-Pliocene (San Gorgonio Pass exposures after Allen, 1957; Lower Coachella Valley exposures after Dibblee, 1954).

clinal upwelling of the Coachella Valley sedimentary fill along the San Andreas fault zone" (Dibblee, 1954, p. 26). It is probable that the marine beds thin rapidly as they approach the mountain front, and are very likely not present north of the Mission Creek fault, as suggested in fig. 4.

Garnet Hill exposure. The Imperial Formation is extensively exposed on Garnet Hill. Previous writers (Woodring, 1931, p. 11; Bramkamp, 1934, p. 24) have mentioned caliche-soaked sediments containing numerous shell fragments of Imperial age on the south side of Garnet Hill, but no outcrops. As exposed in small canyons around the southern rim of Garnet Hill, the Imperial Formation consists of two types of rocks: friable white sandstone, and poorly indurated shale. The shale is dark brown in most exposures but is locally varicolored red and green. It is similar to the fissile claystone in the Indio Hills exposure, except in color.

Only the sandstone member is fossiliferous; it is extremely prolific in pectens and pecten fragments. Inch-thick ostrea valves are also common. The flat, irregular outcrop on top of Garnet Hill is covered by a thin layer of blowsand and ventifacts. Because the Imperial sandstone at this outcrop weathers more readily than the surrounding Cabezon/Ocotillo Conglomerate, deflation has created a closed depression on the top of the hill. Bedding is commonly obscure, giving the sandstone a massive appearance, although rude layering is occasionally seen where sandstone beds grade into sandy siltstone lenses. Subangular quartz grains as much as 0.5 mm in diameter comprise 60 percent of the sands. The remainder is a compact, white matrix including small grains of feldspar, flakes of biotite and muscovite, pyroxene, and chlorite cemented by lime from the disintegrating shells. In addition, the abundance of calcium carbonate, with the help of vadose waters, has cemented the overlying conglomerate and created numerous ¼- to 3-inch-thick caliche hardpans which hold surficial boulders in place.

A gray tuff bed 2 feet thick crops out in the Imperial Formation on the south-central slope of Garnet Hill, and is conformable with the bedding over a distance of 700 feet. The tuff was apparently deposited on the Imperial Sea.

A slight angular unconformity separates these Imperial beds from the overlying Cabezon/Ocotillo Conglomerate. The wide variation in lithology and color of the Imperial Formation here, suggest that erosion and weathering of the sequence occurred before the conglomerate capped the Imperial beds (structure section F-F').

Modified from a list by Woodring (1932, p. 13), a few of the more common fossils found are:

Ostrea heermanni Conrad
Pecten sp., *Pecten* (*Plogiocentrum*) *deserti* (?)
Glycymeris (?)
Corbula
Spondylus
Clypeaster deserti

Painted Hill exposure. Exposures of the Imperial Formation at Painted Hill were first mapped by Allen (1957, Plate 4). Here the beds alternately thin and thicken from 6 inches to 100 feet. They continue

beyond the mapped area to the San Andreas fault where they are truncated. (Near the fault the beds are overturned as much as 45°, by a high angle thrust which has brought up rocks of the San Gorgonio complex on the west.)

Just north of the fault the Imperial Formation is bounded on the west by the channeled, underlying Coachella Conglomerate with an angular discordance of as much as 60° and on the east by the interfingering, conformably overlying Painted Hill Formation. Where the Imperial beds pinch out may be the position of the ancient shore line; here the beds are composed of coarse quartz-rich sandstone. The sediments consist of micaceous siltstone, shale, and sandstone in shades of dark yellow, light brown, and dull green. Thin, irregular gypsum stringers are numerous. Locally the litter of shells and shell fragments is so abundant as to give the impression of a sudden hail storm.

Bramkamp (1934, p. 43) lists the environments of some common adaptive fossils present in the more basal beds of the Imperial Formation, as at Painted Hill:

(1) Fixed forms which are represented by *Ostrea*, *pectens* (partially fixed), *Spondylus*, and *bornocles*; (2) rock clingers such as *Conus* and *Turbo*; and (3) burrowers which are represented by *Eucrosatello*.

In addition, he gives an exhaustive list, with illustrations, of fossils found here by himself and Woodring (1932, p. 12).

Age and correlation. In these three outcrops the Imperial Formation differs somewhat but is always recognizable because of its lithology—either siltstone, claystone, or sandstone or a characteristic gray-yellow or green color. All three outcrops are fossiliferous, and consist of a brackish to near-shore marine tropical fauna which is best correlated with the contemporary Caribbean fauna (Bramkamp, 1934). The formation represents a single incursion of an ancient Gulf of California sea that apparently filled the entire Colorado Desert area with warm littoral and neritic water. This sea never mingled with the Pacific Ocean through the northwest, as the faunas of equivalent age (Jalisco megafaunal stage) west of the Peninsular Ranges are very different (Durham, 1950, p. 6, et al).

Although Woodring (1932) and Bramkamp (1934) believed fauna in the Imperial Formation to be late Miocene, later writers (Wilson, 1948, p. 1770-80; Durham, 1950, p. 30-34) concluded the age to be lower Pliocene.

Sedimentation rates of later formations also suggest a Pliocene rather than Miocene age for the Imperial Formation. The terrestrial Palm Springs Formation, which conformably overlies the Imperial Formation, contains lower Pleistocene fossils, well below the top of the unit. If the Imperial fauna were late Miocene, the Palm Spring Formation would have been accumulating throughout the whole Pliocene epoch and well into early Pleistocene time—a span of about 11 million years, for a maximum of only 6,500 feet of sediments. But in only a few hundred thousand years, the late Pleistocene Ocotillo Conglomerate accumulated 2,400 feet of sediments in the same basin, in a much drier climate. Therefore, it seems far more likely that the

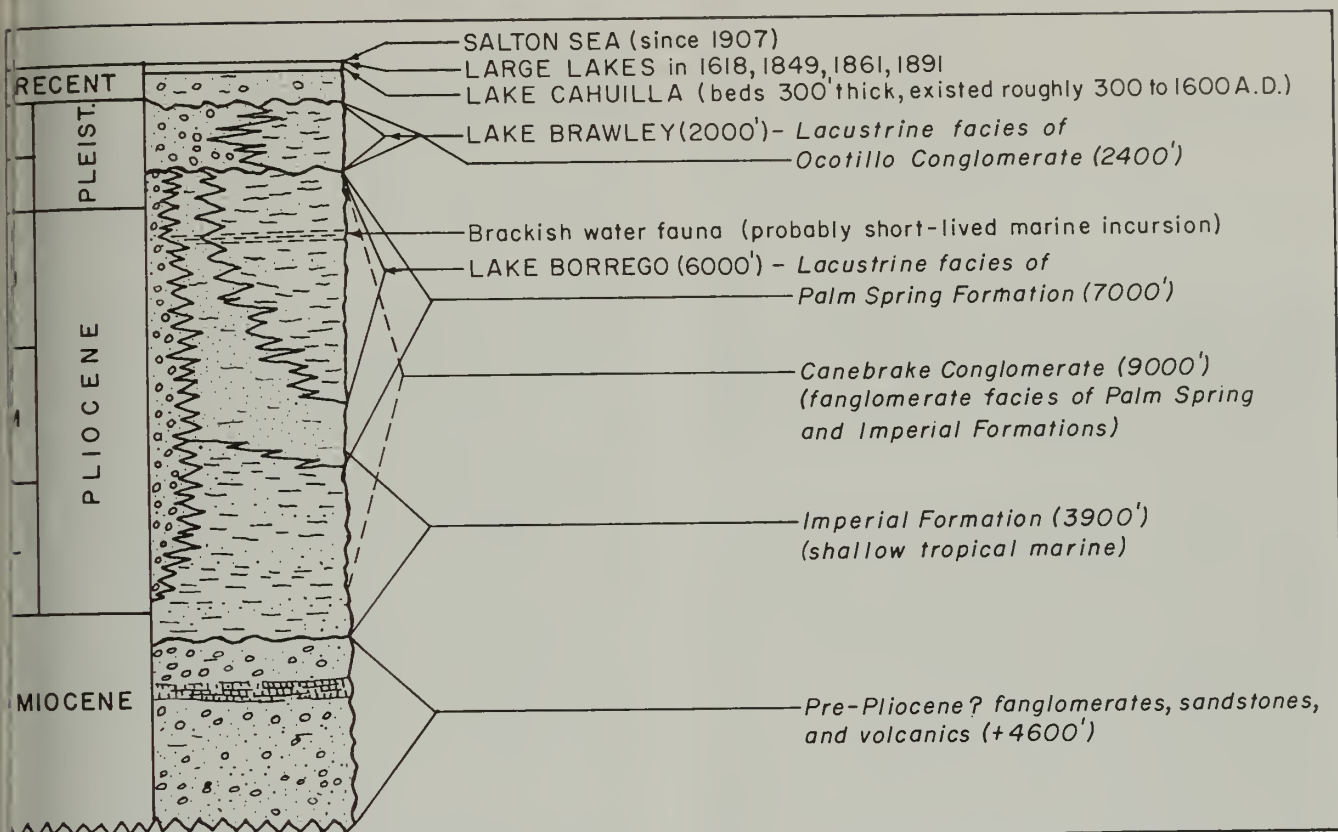


Figure 5. Generalized column of Late Cenozoic lakes in the Colorado Desert with maximum stratigraphic thicknesses. Data mainly from Dibblee (1954), but also from Stearns (1879), and Preston (1893).

alm Spring sediments were accumulating only through a small part of the Pliocene and the Imperial formation conformably beneath it would have to be Pliocene. This argument supports the author's concurrence with the paleontological evidence that the Imperial Formation is lower Pliocene.

Origin of the Imperial Sea. Woodring (1932, p. 9), in discussing the basal Imperial Formation, writes that the change in lithology is abrupt from the underlying "coarse detrital debris" (Split Mountain Formation?) to a considerable thickness of silt:

It is improbable that the material was suddenly furnished by the land areas that had been supplying the underlying coarse detrital debris. If this source is eliminated, the only apparent source is the ancient Colorado River; perhaps they represent the first recorded invasion of the Colorado into the Colorado Desert . . . Perhaps the absence of fossils throughout a great part of the section may be attributed to particularly rapid increments of silt that smothered colonies that had succeeded in establishing themselves.

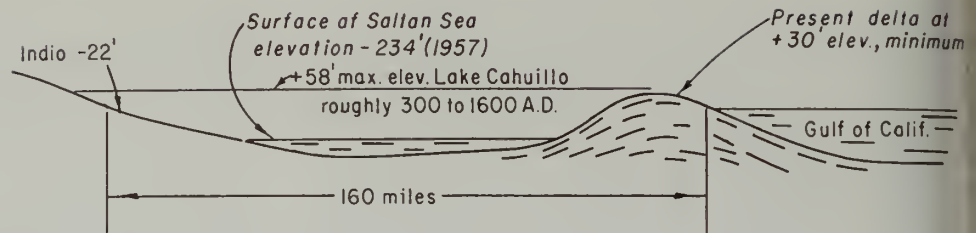
But which came first, the river invasion or the lower advance of the sea? Might not this first river invasion have been similar to the shift of the Colorado River in 1905, when the channel moved northward from an outlet in the Gulf of California to the Imperial Valley depression, and formed Salton Sea? If a depression existed in the Pliocene Imperial Valley, and the river did shift, the depression could have filled with water in a few years. It then could have overflowed the delta-levee (now only 30 feet above sea level at its lowest point), and eroded a channel for ingress of the marine Gulf water.

A similar situation may have occurred at extinct Lake Cahuilla (also spelled Coahuila, and sometimes called Lake LeConte or Blake Sea), which completely evaporated only three to four hundred years ago. Its shoreline is still definable at elevations 30 to 58 feet above sea level in the Imperial Valley and southwestern Coachella Valley; excellent photographs were taken by Mendenhall in 1909. This lake was formed with fresh water from the Colorado River just as the Salton Sea was formed. The river then shifted its course back to the south, leaving the lake to disappear through evaporation. Longwell (1954, p. 53) states that "perhaps erosion by overflow from the lake reduced the height of the [delta-] barrier." This erosion could not have continued for long, or the Gulf of California would have entered and inundated the Imperial Valley to a point north of the town of Indio—160 miles inland!

Even more recent was the sudden formation of "Salton Lake" (Salton Sea) in June 1891 (Preston, 1893, p. 389), caused by a breaching of natural levees on the lower Colorado River. This lake was 30 miles long and averaged 10 miles wide. Twelve years before the levee broke to form Salton Sea, Mr. Preston had prophetically written (p. 392): "To avoid any such contingency it would require but little correction of the banks of the river".

Possibly the simpler mechanism of subsidence and marine inundation is the preferred explanation for the environment of the Imperial Formation. If so, the thicknesses of fossil-barren siltstone in the formation

Figure 6. Profile on Colorado River delta and Salton Sink.



would represent abnormal deltaic deposition in the Imperial Sea. Subsidence and deposition have progressed almost continuously in the Salton trough during and since Miocene time, resulting in more than 20,000 feet of sedimentary fill, as indicated by seismic data (Dibblee, 1954, p. 22).

Pliocene-Pleistocene Series

Palm Spring, Painted Hill Formations; Canebrake Conglomerate

These three terrestrial formations are discussed together to point out their similarities rather than their differences—especially the Painted Hill Formation and the Canebrake Conglomerate. The writer believes they are equivalents, and usage of the younger name (Painted Hill) should be discontinued.

The Palm Spring Formation was named by Woodring (1932, p. 10) when he replaced the preoccupied name "Indio Formation", that had been proposed by Buwalda and Stanton (1930, p. 104-6) after a locality in the southern Indio Hills. Woodring designated Vallecito Creek, a tributary of Carrizo Creek southwest of Salton Sea, as type locality for the Palm Spring Formation and named it after an oasis there.

The Painted Hill Formation was named and described by Allen in 1957 (p. 328-329). Its type locality is at the western edge of the geologic map where Painted Hill conglomerate beds conformably overlie the Imperial Formation just north of its truncation by the San Andreas (Banning) fault. Allen (1957, Pl. 3) has also mapped the Painted Hill Formation abutting the south of the San Andreas fault at a locality 15 miles to the west of the type locality. This large lateral displacement may or may not be post early Pliocene. The most recent fault movement in this area is described by Allen (1957, Pl. 1) as thrusting rather than strike-slip.

When working in the Imperial Valley in 1944, 12 years after Woodring, Dibblee (1954, p. 23) mapped separately the coarse marginal torrential facies of the Palm Spring Formation, and named it the Canebrake Conglomerate after Canebrake Wash. The type locality is at the southeastern base of the Vallecito Mountains southwest of Salton Sea, 3 miles west of Fish Creek Wash, where the conglomerate is about 7,000 feet thick. The more sandy and silty Palm Spring Formation interfingers and grades into the Canebrake Conglomerate westward toward the mountains. It is this torrential, conglomeratic facies of the Canebrake that in every way appears to be similar to the Painted Hill Formation.

Stratigraphy of Palm Spring Formation. Siltstone and sandstone beds of the Palm Spring Formation crop out in a narrow canyon in the northwestern Indio

Hills, and the exposure fans out eastward in a large badlands area. In this exposure, the Palm Spring beds are intensely folded and are commonly near vertical. The interfingering contact with the penecontemporaneous Canebrake Conglomerate is shown in detail on the geologic map, but the contact is also gradational in large part. The Palm Spring rocks are truncated by the flatter lying Ocotillo Conglomerate, thus indicating that major folding, uplift, and erosion took place after Palm Spring deposition, but prior to Ocotillo deposition.

The Palm Spring sediments consist of dark brown siltstones and claystones, with coarse-grained light brown and gray arkosic sandstones prevalent at the gradational contact with the Canebrake Conglomerate. Thin stringers of pebble conglomerate interfinger at the western part of the exposure and commonly grade into typical Canebrake sediments, but also are present as lenses entirely within the Palm Spring Formation. The claystone beds are generally contorted—especially where they are sandwiched between two competent sandstone beds (fig. 7)—and weather into friable pseudoconchoidal chips showing slickensides. Minute quartz grains and biotite flakes were observed with the hand lens; limonite or jarosite coats some beds, helping to define crenulation.

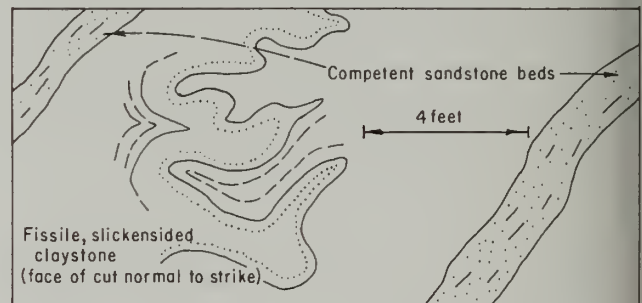


Figure 7. Sketch of contortion of claystone in Palm Spring Formation, northwestern Indio Hills.

The uppermost portions of the Imperial Formation that are exposed in the Indio Hills and at Garnet Hill are predominantly nonfossiliferous siltstone and claystone, as are the lower portions of the Palm Spring Formation. This lithologic similarity suggests that these sediments may have been derived from repeated outpourings of silt from the ancestral Colorado River, and other rivers surrounding the Salton Basin, into the last stages of the Imperial Sea. The disappearance of the Imperial Sea was caused by gradual uplift in the western portion of the basin, and redirection of the ancestral Colorado River into the Gulf of California,

where it presumably continued to deposit deltaic material. If the Imperial Sea was ponded in its final stage, these river sediments would account for the abundance of siltstone in the lower Palm Spring Formation and for the interfingering of the lower Palm Spring Formation with the coarser material of the Canebrake conglomerate facies.

Palm Spring sediments are encountered at depth in the "Edom" oil well south of the San Andreas fault where their estimated thickness is about 1,500 feet. No definite boundary was interpreted for the top of the Palm Spring Formation, because the basal Ocotillo is very sandy and lithologically somewhat similar. Electric logs by the Texas Company also failed to detect a definite contact. Between well depths 2,651 and 2,659 was found a brackish water fauna which suggests a short-lived incursion of a post-Imperial sea, or possibly a northern extension of the lacustrine Borrego Formation. Dibblee (1954, p. 24) mapped the Borrego Formation as the lacustrine facies of the Palm Spring Formation. These possibly Borrego sediments, which are rich in saline minerals, may represent a previously unknown late Pliocene saline lake which antedates Upper Pleistocene Brawley lake beds (fig. 5).

The total thickness of the Palm Spring Formation in the northwestern Indio Hills just south of the Mission Creek fault is close to 2,000 feet, but at the southeastern end of the Indio Hills it thickens to about 3,300 feet (Dibblee, 1954, p. 24).

On Garnet Hill the Palm Spring Formation was eroded off the underlying Imperial Formation prior to deposition of Cabezon Fanglomerate. However, Palm Spring rocks are believed to underlie the fanglomerate unconformably farther north, as shown in structure section F-F'.

Stratigraphy of Painted Hill Formation. Measured south of structure section B-B', the Painted Hill Formation is 3,400 feet thick, and consists of gray and buff poorly sorted beds of conglomerate, and arkosic conglomerate sandstone. The clasts are subrounded, and average about a foot in diameter, but larger ones are common. Although the rock is poorly consolidated, two subparallel resistant conglomerate beds form a steep ridge (unit Pphc on map) about 300 feet above the base of the section, and can be traced easily for more than a mile. The clasts at this locality are dominantly basalt derived from flows in the Coachella Formation, but gneiss, granitic rocks of intermediate composition, and pegmatite clasts become more abundant higher in the section.

A thin olivine basalt flow at Devil's Garden can be traced for a few hundred feet along strike. Its composition and texture are very similar to the basalt in the Coachella Formation, but it is more vesicular and contains half-inch amygdulites of dull green decomposed opal, and some of calcite. This flow is late Pleistocene and represents the most recent evidence of volcanic activity in the Coachella Valley.

The contacts of the Painted Hill Conglomerate with the underlying Coachella Fanglomerate, and with the overlying Cabezon Fanglomerate are everywhere difficult to distinguish accurately. The uncertain contacts shown are chiefly after Allen (1957, Plate 4), who

states (p. 328) they are "located on the basis of changes in dip along the unconformity".

Stratigraphy of Canebrake Conglomerate. This fanglomerate-conglomerate crops out in the northwesternmost canyon of the Indio Hills. It interfingers and grades laterally and vertically into the Palm Spring Formation toward the east.

The Canebrake Conglomerate is rather obscurely bedded, massive, ill-sorted, and generally extremely well indurated into a "natural concrete" in which fracturing breaks through rather than around the clasts. The conglomerate consists of grit, pebbles, cobbles, and occasionally boulders approaching 2 feet in diameter, set in a coarse sandy matrix of quartz, feldspar, and biotite grains. Minor accessory minerals include pyroxene, garnet, epidote, sphene, and rutile. Matrices become silty and less indurated as one approaches a gradational contact with the Palm Spring sediments. The clasts show a high degree of roundness and sphericity, and many are highly polished. Gneisses comprise 70 to 80 percent of the clasts, the remainder are quartz monzonite, biotite quartz diorite, and about 5 percent basic andesite porphyries and olivine basalts. A few pegmatite clasts were observed, one containing an inch-long euhedron of black tourmaline. No correlation appears between size, roundness, and composition, but schistose clasts weathered from metasedimentary gneiss form tabular clasts with rounded edges. The conglomerate as a whole is light tan, which makes it difficult to distinguish from the overlying Ocotillo Conglomerate.

A source area to the west for the Canebrake sediments is suggested by the fact that the nearest known source for its volcanic clasts is the Coachella basalt exposed 12½ miles northwest of the Indio Hills, in the foothills of the San Bernardino Mountains. In addition, the great majority of clasts are well-rounded to subrounded, indicating they have traveled several miles, at least. Because very little conglomerate was encountered in the "Edom" oil well in the Palm Spring section, it seems probable that the Canebrake Conglomerate interfingers and lenses out across an east-west boundary also.

Age and correlation. The Painted Hill Formation, Palm Spring Formation and, elsewhere in the Colorado Desert, the Canebrake Conglomerate, all conformably overlie the lower Pliocene Imperial Formation, and all are unconformably overlain by Quaternary fanglomerates—Cabezon in the western Coachella Valley, Ocotillo in the east. The discovery by Frank W. Popenoe in 1958 of Upper Blancan (lowermost Pleistocene) horse remains in the Palm Spring Formation in the Indio Hills indicates that the formation probably spans the time from mid-Pliocene through early Pleistocene. (Premolar 4, molars 1, 2, 3, fragments of cheek teeth, and one each radius and ulna were found by Popenoe, and identified by Dr. Theodore Downs of the Los Angeles County Museum as *Equus* cf. *Plesippus*; the symphysis of the lower jaw, with tooth roots, of a giant camel was also found, but no genus could be affixed.) In the Indio Hills, the Palm Spring beds are vertical and even overturned, probably as a result of later movement by the San Andreas fault.

The uppermost Canebrake beds in western Imperial Valley have yielded mammalian, reptilian, and avian vertebrate fauna (Theodore Downs, 1957, p. 1822-1823, and personal communication, 1958). These are also of earliest Pleistocene age. However, only the lower parts of the Canebrake, Palm Spring, and Painted Hill Formations are exposed in the area of this report, so their ages are older; perhaps middle Pliocene.

No significant fossils have been found in the Painted Hill Formation but its gradational relationship with the underlying Imperial Formation, plus similar lithology and unconformable overlap by late Pleistocene fanglomerate suggest an age span similar to that of the Canebrake Conglomerate. The writer believes that they are the same unit.

The point is again stressed that the writer believes that the Colorado Desert depression has existed in essentially the same position since Miocene time with relatively minor fluctuations, and always with a rim of mountains or hills yielding debris into a basin. However, late Tertiary deformation, including large strike-slip displacement, is probably responsible for the present configuration of the basin.

Quaternary System

Cabazon Fanglomerate and Ocotilla Conglomerate

The Quaternary Cabazon Fanglomerate was named and described by Vaughan in 1922 (p. 387-392) although he included rock units in it later dated as Pliocene. It is exposed from Millard Canyon, 10 miles west of the geologic map, eastward to Whitewater Hill, thence northward forming the base of the foothills of the San Bernardino Mountains, and into Morongo Valley. Garnet Hill is a folded outlier in the middle of the Coachella Valley, and Dever's Hill is a remnant of a fan partially covered by Recent alluvium.

The Ocotillo Conglomerate was named and described by Dibblee in 1954 (p. 24, 25). It crops out extensively throughout the northwestern Imperial and northeastern Coachella Valleys. The type section is in the northern part of the Borrego Badlands, west of Salton Sea. In the western Indio Hills it is covered by blowsand and occasional ventifacts.

Stratigraphy of Cabazon Fanglomerate. As exposed on the erosion scarp on the south side of Whitewater Hill, the fanglomerate consists of ill-sorted, poorly bedded, pebbly and bouldery tan arkosic sandstone with clasts of gneiss (50 percent), granitic rocks and pegmatite (45 percent), and a minor amount of basalt (photo 5). The granitic clasts were evidently derived from far within the northern San Bernardino Mountains, where Cactus Granite is prevalent (Vaughan, 1922), and deposited here as fans by the ancestral Whitewater River. Warping and re-excavation of the fans, and landsliding, have subsequently exposed the Cabazon rocks here.

Allen (1957, p. 331) noted a 30-foot thick lens of light gray limestone breccia interbedded with the Cabazon Fanglomerate on Whitewater Hill, and observed that it was probably derived from one of the limestone beds in the northeastern San Jacinto Mountains. This breccia is the only sedimentary rock on the north side of San Geronio Pass that appears to

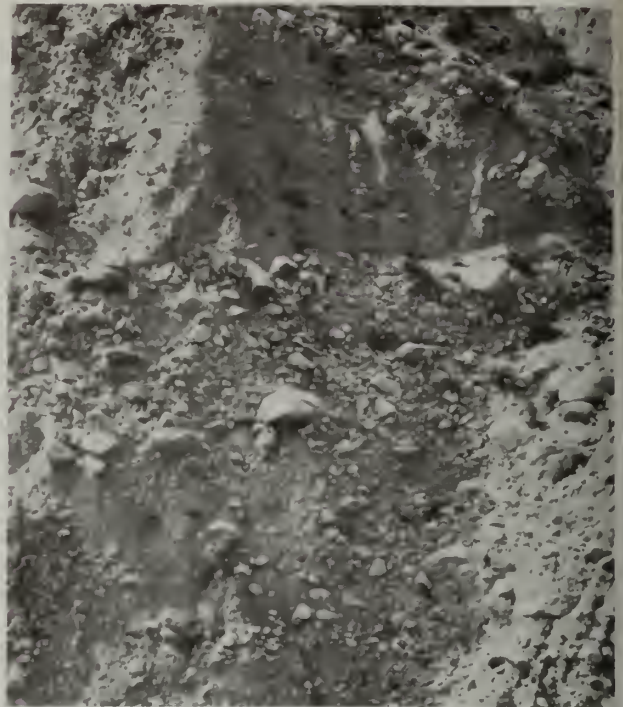


Photo 5. Closeup of Cabazon Fanglomerate exposed at Whitewater Hill showing rude bedding of sandy and conglomeratic lenses. Boulders reach 19 feet in maximum diameter.

contain a significant amount of material derived from the San Jacinto block.

However, ventifacts of siliceous, impure limestone are found on Garnet Hill and, to a lesser degree, on the western Indio Hills; in addition, most of the fanglomerate clasts strewn over Garnet Hill are diorite and granodiorite, similar to rock types found in the San Jacinto Mountains. These occurrences suggest that drainage off the northern San Jacinto block has only rarely extended to the north, and has since late Tertiary time dominantly drained eastward, as at present.

The size of the clasts in the Cabazon Fanglomerate ranges from large boulders to sand, but averages about 6 inches. The largest boulder observed on Garnet Hill, resting on Imperial siltstone, measured 19 feet in maximum diameter. On Whitewater Hill, in Long Canyon, and in Dry Morongo Wash, clasts larger than 10 feet were found, all showing extreme desert varnish and polish. Most clasts in the fanglomerate are subrounded, but on Garnet Hill they are generally angular; here, too, they are cemented with white caliche, evidently derived from the underlying Imperial Formation, instead of with common clay and silica as in other exposures.

In White House Canyon, the fanglomerate grades upward from sandy, pebble-cobble conglomerate into a coarse bouldery conglomerate. Near the mouth of the canyon, these members are separated by a local angular unconformity in conjunction with a normal fault, although the clast size and degree of induration above and below the unconformity are identical.

In Big Morongo Canyon, at the gneiss-fanglomerate contact on the Morongo reverse fault, the conglomerate is indurated to a reddish brown natural concrete.

This induration was apparently created by friction heating along the fault.

Clasts of Cactus Granite and quartz monzonite form most of the Cabezon Fanglomerate northward from Mission Creek Canyon into Morongo Valley. Indeed, the correlation of rock types across the Mission Creek fault is the basis for showing its large vertical displacement here.

Although the base of the formation is not exposed, a thickness of approximately 1,000 feet is preserved on Whitewater Hill; Allen (1957, p. 325) found at least 1,500 feet a few miles west of the area of this report.

Stratigraphy of Ocotillo Conglomerate. The light tan Ocotillo Conglomerate, as exposed in the Indio Hills, is generally sandier than the typical Cabezon Fanglomerate, and the clasts are smaller, averaging pebble and cobble size. They are subrounded, and consist of locally derived gneisses (70 percent), granite (20 percent), with the remainder of basic volcanic rocks, impure limestone, and pegmatite.

The Ocotillo conglomerate is considerably more folded in the southern part of the mapped area than in the north, and the attitudes are generally much less steep than in the underlying Imperial Formation. In the canyon south of the Mission Creek fault, the Ocotillo Conglomerate dips gently northeast and overlies the Canebrake and Palm Spring Formations with an angular discordance of as much as 80°. Abutting the San Andreas fault on the north are several ridges of indistinctly bedded, well-indurated arkosic Ocotillo sandstone (Qos), which form the limbs of a syncline. The strata within the fault zone are noticeably deformed and tilted at various angles.

The "Edom" well intersected approximately 2,400 feet of Ocotillo beds—only 300 feet more than Dibblee (1954, p. 25) estimated in other parts of the Indio Hills, and may be close to the maximum thickness for the formation.

Age and correlation. The Ocotillo Conglomerate unconformably overlies the Canebrake and Palm Spring Formations, in which lowermost Pleistocene fossils have been found. The Cabezon Fanglomerate is similar to the Ocotillo Conglomerate in provenance, general lithology, color, degree of induration, and degree of deformation. The Cabezon beds also have similar stratigraphic position, being unconformably underlain by Canebrake Conglomerate ("Painted Hill Formation").

Allen (1957, p. 330) believes the Cabezon Fanglomerate is correlative with the uppermost (Pleistocene) San Timoteo (?) Formation of western San Gorgonio Pass, on the basis of similar stratigraphic position, and because the San Timoteo (?) beds coarsen toward the top of the section and include granitic clasts similar to those in the Cabezon Fanglomerate. Even though these exposures are nowhere less than three miles apart, with no intervening fanglomerate, this correlation seems valid to the author.

Terrace deposits

The stream terrace deposits shown on the geologic map are Recent thin mantles and patches capping older rocks. Usually these patches are a few inches

to a few feet thick with large boulders standing out above the gravel and sand of the matrix. Most smaller fragments are subangular and resemble alluvium, except that alluvium is everywhere pale gray-brown. The large boulders, the last vestige of once-extensive terrace deposits, are generally well rounded and polished, owing mainly to mechanical weathering caused by strong desert winds and extremes in temperature. In most places, terrace deposits weather to form a bright orange colored soil.

On Whitewater Hill, the terrace deposits are being slowly eroded off the Cabezon Fanglomerate on the north slope. Allen (1957, p. 344) observed these terrace deposits as a "semi-concordant capping of weathered material", but he included it with the Cabezon Fanglomerate.

In Little Morongo and Long Canyons, patches of terrace deposits are perched 20 to 100 feet above the present stream channels and contain occasional boulders as much as 10 feet in diameter. It is not possible to discern if these patches are the last remains of Cabezon Fanglomerate or are later stream deposits.

In Dry Morongo Canyon (Morongo Valley Canyon) on a steep slope next to Twentynine Palms Highway, a peculiar patch of well indurated, silica-cemented conglomerate 80 feet long, 20 feet wide, and 4 feet thick, is precariously attached to the underlying gneiss with a flat, uniform depositional contact that dips 47° southward with the slope of the mountain. Clasts average 2 inches in diameter and are extremely well rounded and polished. The silica cement may have been spring deposited; no similar deposits were found in the area.

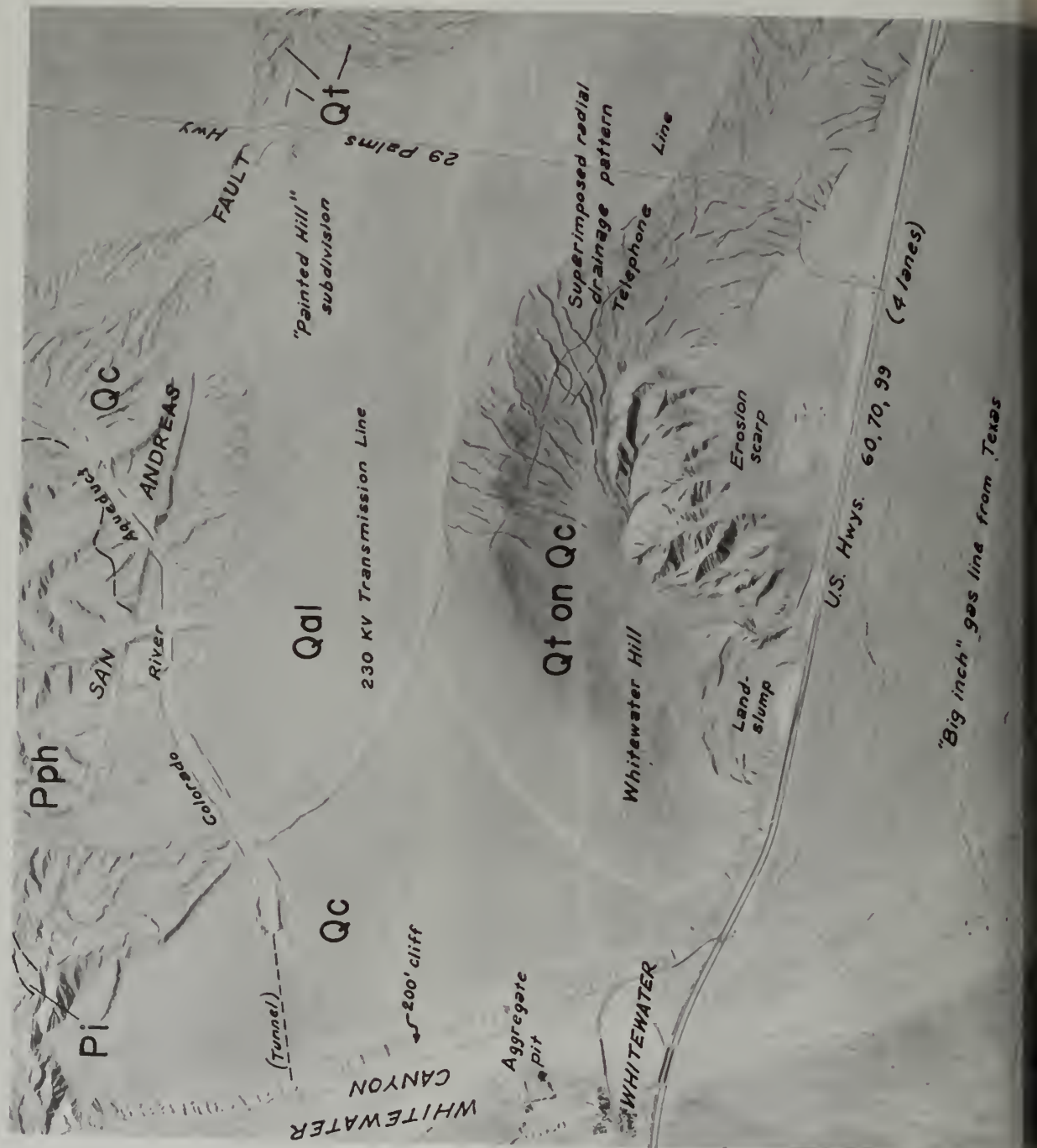
Alluvium

The contact between alluvium and superficial sand deposits in some places is sharp, as around the San Jacinto Mountain spurs, but more commonly it is a gradational boundary. It is certainly a shifting boundary, due to fluctuations in intensity and direction of the winds, which distribute the superficial materials. Towards the valley from the washes and arroyos—which tend to be sandy in their lower reaches—the alluvium is more compact and has a marked increase of silt, which eventually weathers to form a desert soil.

The alluvium in Dry, Big, and Little Morongo Canyons extends through the Little San Bernardino Mountains and is derived mainly from the high, east flank of the San Bernardino Mountains where precipitation is relatively high. This is substantiated by the occurrence in the alluvium of the uppermost Coachella Valley of pebbles of crystalline limestone that must have come from the Furnace Limestone, now being eroded by the headwaters of Little Morongo and Mission Creeks 15 miles northwest of here (Vaughan, 1922, p. 355).

Superficial Sand

Wind-blown sand is very common in the Coachella Valley; three main types of occurrences are marked on the geologic map: (1) Where sand settles on the leeward side of hills and ridges, as at Windy Point in the San Jacinto Mountains, irregular patches on Garnet



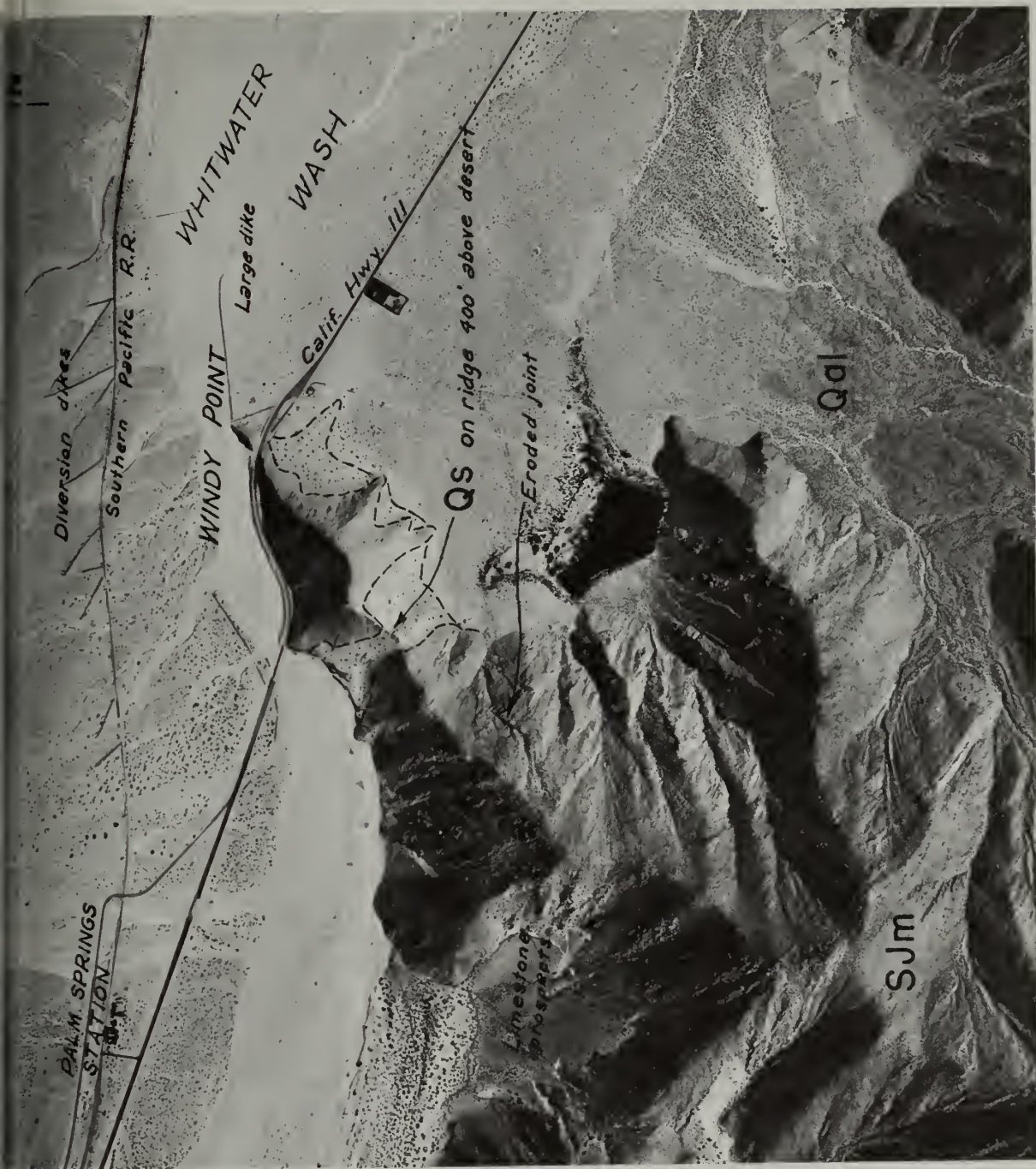


Photo-mop 1. Aerial photo-mop of San Geronimo Pass at southwest corner of oreo, including a strip 1 mile west of geologic map. Cultural geography and surface geomorphology is also shown. The top aerial photo, by U.S. Department of Agriculture, is of 1:24,000 scale; the bottom, by Fairchild Aerial Surveys, Inc., is 1:18,000. Geologic symbols explained on plate 1.



Photo 6. View from atop Windy Point looking south. Oddly enough, the gentle slope of the sand dune in the foreground is leeward to the dominant wind direction and the steep front is windward (facing west). The elevation here is 400 feet above the pass floor. Note large solution-erosion limestone joint in background.

Hill, and patches on a ridge of the Little San Bernardino Mountains 2,000 feet above the valley floor. (2) Where sand settles on windward slopes, as on the western slopes of the Indio Hills, and again, on Windy Point (Photo 6). (3) Where sand is caught and held by vegetation, as by the brushland along the north side of the San Andreas fault in Seven Palms Valley.

Stream deposited sand is also abundant, mainly in the numerous washes. Russell (1932, p. 86) writes

Since climatic conditions are such as to permit only on ineffectual vegetational cover along the lower foothill belt, denudation and erosion are rapid . . . and debris is furnished in huge amounts to the (desert) floor . . . Each flood brings more sand to the washes, replacing that blown away since the last flood.

Lithology. Three samples of sands from nearby localities—the Whitewater River bed; a 15-foot dune at Myoma Station, 18 miles southeast of Garnet Hill, and the lee side of Edom Hill, 1 mile southeast of this map—were described by Ralph Reed (1930), and compared to other Recent sands in California. After studying samples of sand from Seven Palms Valley and the western Indio Hills, the writer concurs with his conclusions: quartz, surprisingly, is second in abundance to fresh-looking feldspar. Biotite is so abundant as to form 18 percent of one sample and commonly appears to be even more abundant. Epidote,

sphene, zircon, garnet and especially hornblende, are also prevalent. Commonly the largest grains consist of gneiss, with many minerals visible in a single grain. All grains are angular or subangular, indicating that the sands are immature and freshly supplied. Windward slopes expose gravel and pebble surfaces strewn with ventifacts. Many sandy surfaces are covered with grains averaging 3 mm in diameter, but a few inches down, smaller grains are found, accompanied by much silt and biotite flakes; the average grain diameter is 2 mm.

The Whitewater River and its tributaries supply all the mapped area's alluvial sand, mostly derived from intermediate to basic gneisses and igneous rocks. The southwestern part of the Coachella Valley, from the mouth of San Geronio Pass to Indio, is blanketed with wind-blown sand, whereas the northern and eastern parts have little or no sand cover. An active embryonic dune area of approximately 40 square miles extends from the southwest Indio Hills to just west of Indio.

STRUCTURE

Faults

Regional setting

The San Andreas fault is one of the most widely known structural features of the western United States. It is a through-going zone of weakness that has been traced from the Gulf of California in Mexico more than 700 miles to Point Arena, Mendocino County, where it plunges into the Pacific Ocean. Seismographs constantly record small earthquakes along it, proving that it is an active fault; one major earthquake centered near Desert Hot Springs in 1948 is described below. The fault zone ranges in width from Recent scarps in alluvium a few inches across, to branching and braiding faults representing a zone 6 miles wide in central California, and some tens of miles wide in southern California. Major problems relating to the San Andreas fault have been discussed by many geologists; conclusions have been summarized by Hill and Dibblee (1953, p. 445):

- (1) the San Andreas is a steep fault zone of variable width consisting of one or several nearly parallel faults; (2) its inception was quite likely pre-Tertiary, and is now active; (3) it has probably been characterized by right lateral displacements throughout its history; (4) it marks such an important contact that rarely can it be crossed, except in Recent alluvium, without passing into significantly different rocks; and (5) its cumulative displacement of some rock units is at least tens of miles, and older rocks may have been displaced a few hundred miles.

South of Cajon Pass, 40 to 60 miles northwest of the area described in this report, the San Andreas fault consists of several great branches which alternately split and merge: the San Jacinto fault on the southwest, and the Mill Creek and associated faults on the northeast, are the limiting breaks between which several major faults lie (fig. 8).

The San Jacinto fault is seismologically one of the most active in the region; it also forms the most prominent fault trace southeastward into Mexico. Noble (1932, p. 360) wrote "It is at present probably the most active fault in southern California. Within historical time it has been much more active than the San Andreas."



Photo 7. Trace of Son Andreas (Banning) fault across Upper Coachella Valley. Oblique aerial view taken above Whitewater Canyon (foreground) toward east. Fault-dommed ground water has caused vegetation to grow only on the north side of fault, for which the term "vegetation scarp" is proposed, as seen in Whitewater Canyon and in Seven Palms Valley west of Indio Hills (center of photo). Note also vegetation on fault trace of Mission Creek fault at center-left of photo.

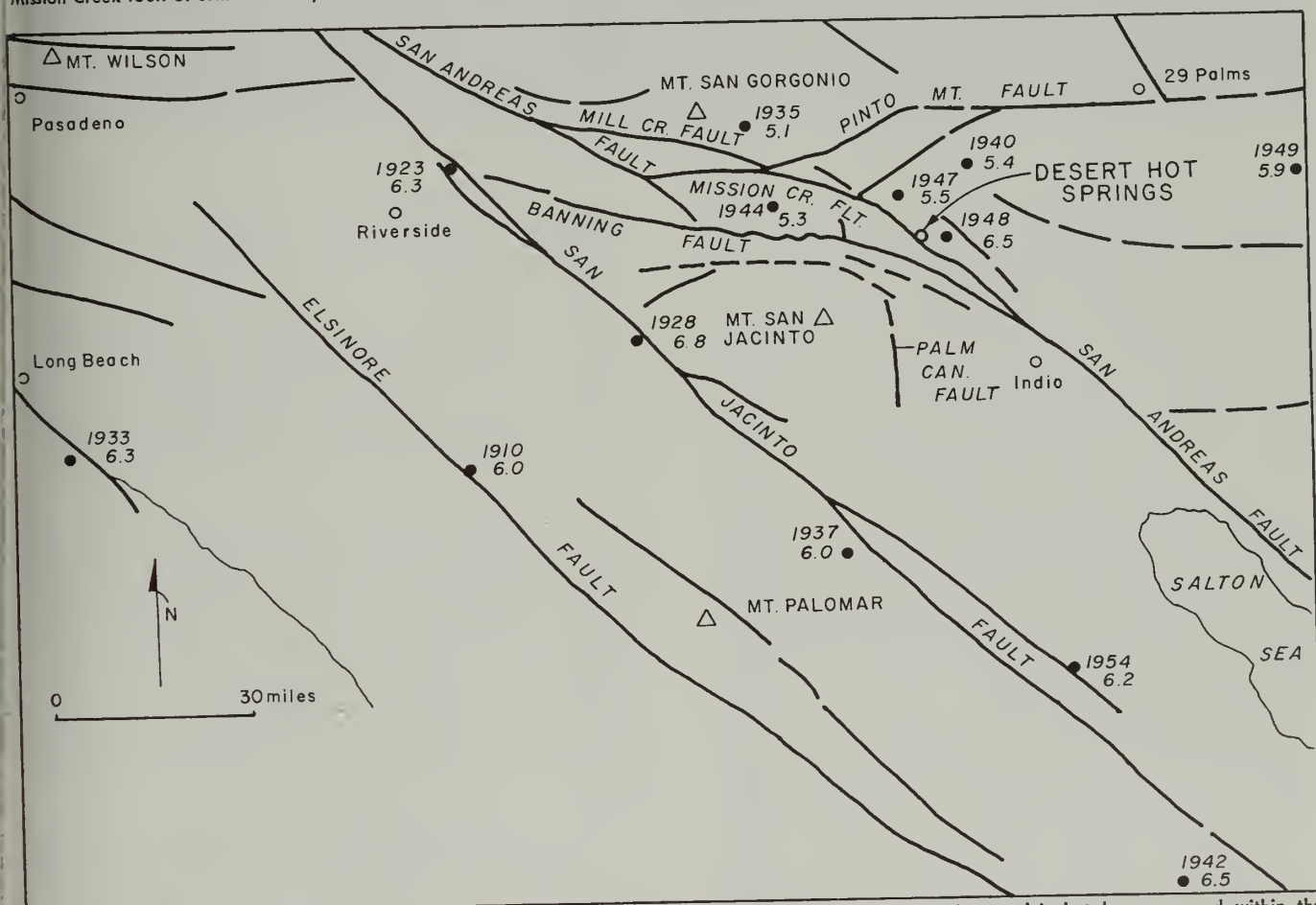


Figure 8. Major faults of southern California showing epicenters of earthquakes 5.9 or greater (Richter scale) that have occurred within the past 50 years. Four additional earthquakes of lesser magnitude in the region around Desert Hot Springs are shown. Data modified from Richter, Allen, and Nordquist, 1958.

The Mill Creek fault, the most northern branch of the San Andreas in this region, is a bold structural feature that cuts laterally across the San Bernardino Mountains just south of San Gorgonio Peak. Near the headwaters of the North Fork of Whitewater River, 7 miles west of the mapped area, the Mill Creek fault appears to fray out and becomes indistinct eastward. It converges with the Mission Creek fault but the nature of the contact is obscured by canyon alluvium. The Pinto Mountain fault (Hill, 1928, p. 146) also merges with the Mission Creek fault at this juncture, but veers off to the northeast where it can be traced as far eastward as Twentynine Palms. Most geologists since Vaughan (1922) have believed the Mill Creek and Mission Creek faults to be separate faults, without connection. This does not mean that they could not have been one and the same fault once, and possibly more deserving of the name San Andreas. As pointed out by Allen (1957, p. 315):

The deformation and disruption of former breaks appears to represent a pattern . . . where elements of San Andreas and Transverse Range structure have been vying for control; evidently one set has alternated with the other in attaining temporary dominance.

Within the San Bernardino Mountains appear several other branch faults of the San Andreas system, but the name "San Andreas" has been traditionally applied to the branch that is most nearly aligned to the general trend and bounds the mountains on the southwest. This fault then turns southeast and ends abruptly just north of the Banning fault, in Potrero Canyon near Banning. Allen (1957) has done much to clear up the complicated structure pattern in the San Gorgonio Pass area. In the distant past, this San Andreas fault clearly was the dominant structural break, and merged with the lesser east-west trending Banning fault. But orogenic activity and Recent thrusting on the Banning fault have caused the San Andreas fault here to become relatively inactive. It may even have become permanently inactive at this time—as have other great faults within the San Andreas system (Crowell, 1958, p. 18). Nevertheless, the author will continue to use the name San Andreas for the eastward extension of the Banning fault beyond San Gorgonio with the understanding that west of the area of this report, the name Banning fault is more appropriate.

Some geologists refer to the Mission Creek fault as the North branch of the San Andreas fault, and the Banning fault as the South branch of the San Andreas fault. This is compatible with the concept that the San Andreas fault is not everywhere a single break but is a non-uniform fault zone. The Mission Creek and San Andreas faults merge at a low angle near Biskra Palms in the Indio Hills, 12 miles southeast of the Desert Hot Springs area.

Regional warping has contributed greatly to the present physiography of the upper Coachella Valley, helping to create such features as the Salton Depression, the arching of San Gorgonio Pass, and the apparent plunge of the San Bernardino Mountains to the east. Regional warping is the primary reason for the uplift of the marine Imperial Formation to the present maximum of 2,500 feet above sea level—a displacement that has transpired since mid-Pliocene time.

San Andreas fault

Physiography. In the mapped area, the San Andreas fault follows a straight, almost undeviating course from the foothills of the San Bernardino Mountains, across the Coachella Valley and into the Indio Hills (Photo 7). Although it strikes east in Whitewater Canyon, the fault trace strikes S. 76° E. at the western edge of the geologic map, and gradually curves southeastward to S. 62° E. in the Indio Hills, 10 miles distant. It can be observed on the desert floor, except in the vicinity of North Palm Springs where very recent alluviation has obscured its trace. In Seven Palms Valley the fault is well defined by vegetation which grows along its north side, where fault-dammed groundwater is brought near the surface; this shows up strikingly on aerial photos. Another result of faulting is an area of artesian wells near Seven Palms Ranch; these are the only artesian wells in the upper Coachella Valley.

From its topographic expression, the fault is clearly seen to be nearly vertical, with a probable steep dip towards the north. Where the fault crosses Twentynine Palms highway, several hummocks of orange-colored terrace gravels have been aligned in a rift-like groove. Where the fault crosses the Colorado River Aqueduct, the San Andreas fault zone was exposed in a construction excavation as an altered zone 55 feet wide in the Pleistocene Cabezon Funglomerate. The boulders are not crushed, but the conglomerate is a slightly different shade of gray-brown than rocks on either side of the zone. Numerous thin caliche stringers crisscross the zone, marking access routes for percolating ground waters.

Displacement. Evidence of large scale vertical or horizontal movements was not found along the San Andreas fault in the mapped area. Rather, the Mission Creek fault appears to be the more active member of the system here.

In the Indio Hills the San Andreas fault trace is strikingly portrayed on aerial photographs and can be determined in the field by disturbed attitudes. Fold and drag structures in Ocotillo Conglomerate beds suggest right-lateral displacement along the fault. In addition, a syncline and an anticline have been abruptly truncated at the fault.

Just west of the Indio Hills, a sand-filled trough appears to be a small graben formed between the main San Andreas fault and one of its branches. The branch fault has uplifted Recent alluvium and late Pleistocene Ocotillo Conglomerate on the south, but the main fault has uplifted the northern block relative to the southern.

In the Mecca Hills, 25 miles southeast of the mapped area, the San Andreas fault occupies a thoroughly crushed zone 300 feet wide, with local dips that range from 15° northeast to nearly vertical (Hays, 1957, pl. 5).

Garnet Hill fault. The buried fault parallel to, and 1½ miles south of, the San Andreas fault is herein named the Garnet Hill fault. The main evidence for this fault is a gravity anomaly survey of the Coachella Valley by a major oil company. Gravity-low contours define a trough here which is almost as well delineated



Photo 8. Rift of San Andreas (Banning) fault looking west across foothills of San Bernardino Mountains. Whitewater Hill at left shows darker colored terrace cover which was deposited before hill was warped up.

as the troughs of the San Andreas and Mission Creek faults; it is especially strong south of Garnet Hill. This fault, undoubtedly an ancestral branch of the San Andreas fault, apparently is an extension of a fault which Allen (1957, Pl. 1) traced in the alluvium of Whitewater Canyon, southwest of Whitewater Hill. Half a mile southeast of the geologic map, a detached sand-surfaced hill is aligned with the projection of the fault trace. Thus, the Garnet Hill fault can be directly and indirectly traced for at least 11 miles.

Dillon fault zone. The subparallel southeast-trending faults in the northeast corner of the area are the westernmost extension of a marked fault zone: the Dillon fault zone. Don Pruss and Gordon Olcott of the Southern Pacific Company, stated (personal communication, April 1958) that a more or less well defined fault zone extends through the Little San Bernardino Mountains southeast of the map area for about 16 miles, where it leaves the mountains and cannot be traced in the alluvium.

The San Andreas fault system in the area mapped is defined on the basis of similar fault strikes (Crowell, 1958, p. 17), to include the area between the Garnet Hill fault and the Dillon fault zone—a width of about 10 miles.

Mission Creek fault

Physiography. The Mission Creek fault, named and first described by Vaughan (1922, p. 401-403), is

believed to be the most active tectonic feature in the map area because of its Recent topographic expression, and seismological data that relate it to recent earthquakes. Previous locations of the Mission Creek fault in the mapped area have been corrected by the writer to a position marked by disrupted alluvium, truncated older fans and a "vegetation scarp" (Photos 7 and 8) where fault-dammed ground water has stimulated growth on the north side of the fault.

The location and sense of movement of the Mission Creek fault, like others in this region, is also known from such indirect evidence as gravimetric survey results, water well depths to water table (see below), seismic data (see below), and movement measurements from precise triangulation surveys of the U.S. Coast and Geodetic Survey (Whitten, 1955).

The fault planes of the Mission Creek fault and its branches steepen from west to east: at the western edge of the map, on a ridge $2\frac{1}{2}$ miles west of Twentynine Palms highway, the main fault plane dips 62° northward (Allen, 1957, Pl. 1); at the mouth of Big Morongo Canyon a branch fault dips 80° northerly; and at White House Canyon a minor branch fault dips 74° northerly. In the Indio Hills, the nearly straight trace of the Mission Creek fault indicates a near-vertical dip. The Mission Creek fault trace strikes east-west at the western edge of the area, S. 45° E. at Desert Hot Springs, and S. 55° E. in the Indio Hills at the east margin of the map area.

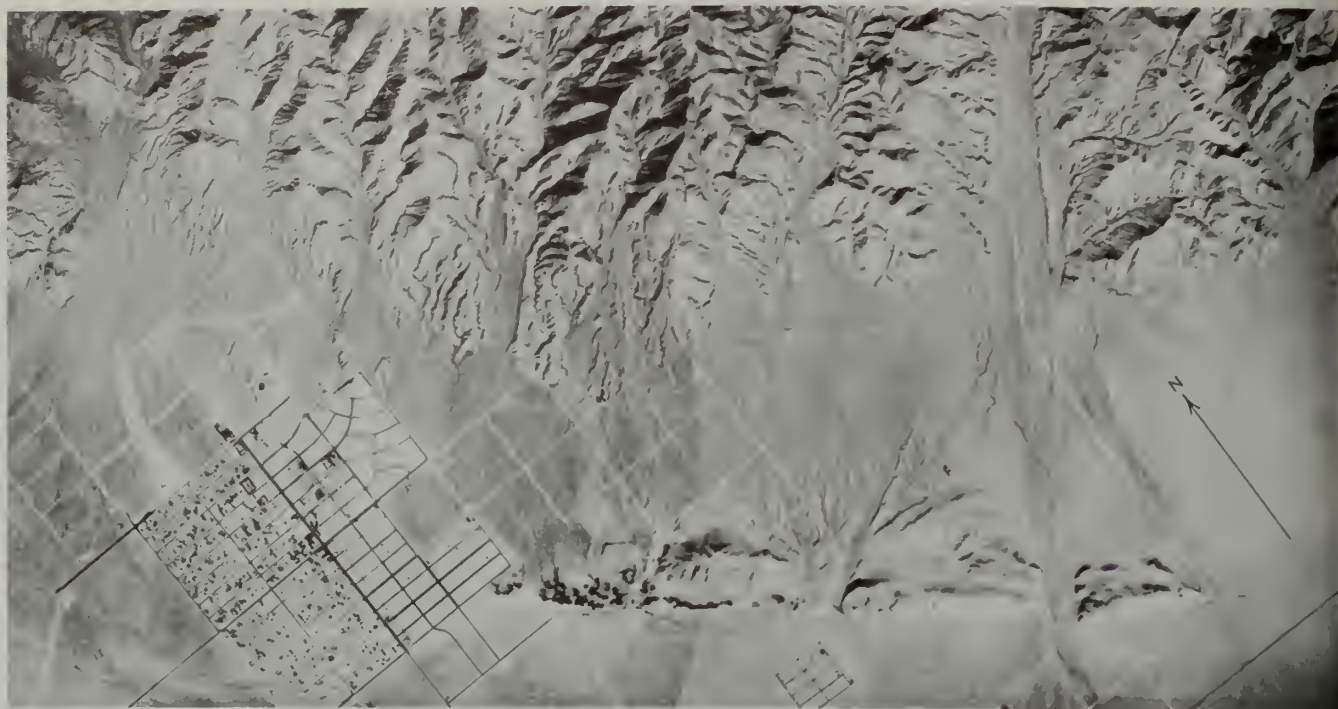


Photo 9. Vertical aerial photograph taken in 1953 of the town of Desert Hot Springs showing the Mission Creek fault marked by vegetation and uplifted alluvium fault scarps. Much of the scarp has been subdivided into "view lots." The Blind Canyon fault trace can be seen on terrace fans at left. Scale: 1.4 inches equals 1 mile. Photo by Fairchild Aerial Surveys, Inc., courtesy of The Texas Co., reproduced by permission of C. R. Allen.

West of Twentynine Palms highway the fault is expressed in a high escarpment through green amphibolite gneiss, locally brecciated to cataclasite. Here it is a narrow zone consisting of several breaks with three definite fault traces extending west of the mapped area; the main fault is generally the most southerly of the traces. Where it is a straight line separating gneiss from Cabezon Fanglomerate the fault can be sharply delineated in the field, but where it passes through gneiss in this fractured zone, individual breaks can be plotted only after careful study of stereo-pairs of aerial photos.

The irregular front of the base of the Little San Bernardino Mountains east of White House Canyon is believed to extend as a pediment under the alluvium to the Mission Creek fault, rather than to represent a separate fault. Clarence Allen (personal communication, 1958) agrees and states further (*in* Richter, Allen, and Nordquist, 1958, p. 321) that the strain-release pattern of the Desert Hot Springs earthquakes trends more nearly parallel to the Mission Creek fault than to a hypothetical break along the base of the Little San Bernardino Mountains.

Displacement. Relative displacement of Recent movement on the Mission Creek fault is up on the north block (reverse vertical component), while the strike separation (horizontal component) is right-lateral. Relative movements are summarized in figure 9.

(1) Evidence for reverse displacement is seen on the walls of Mission Creek Canyon where gneiss overlies late Pleistocene Cabezon Fanglomerate at a steep angle. Cabezon Fanglomerate on the mountain plateau north of the canyon is 600 feet above Cabezon Fan-

glomerate south of the main fault. The irregular capping of fanglomerate on the plateau is only some 20 feet thick, a large quantity apparently having been removed by erosion. South of the fault the fanglomerate is at least 500 feet thick, with its basal contact exposed. A minimum throw of 1,100 feet is thus suggested here; net separation would be even greater. (Elevation of the plateau at the time that the fanglomerate was deposited, may have resulted in the thinner layer there; on the other hand, the total thickness of fanglomerate south of the fault may have been much greater than the exposed 500 feet.) This appears to be the largest Recent (post-Cabezon) vertical component of displacement yet reported in the San Andreas fault zone.

However, describing the vicinity of Raywood Flat, 10 miles west of here, Allen (1957, p. 341-342) found that "... the (Mission Creek) fault zone dips 45° north and is characterized by a thickness of pulverized rock exceeding a quarter of a mile ... The covering of unbroken Cabezon (?) fanglomerate ... indicates the absence of Recent movement here."

(2) The uplift of Recent alluvium and fanglomerate as much as 110 feet on the north side of the fault at Miracle Hill, southeast of Desert Hot Springs, is additional evidence of Recent movement in the mapped area.

Buried branches of the Mission Creek fault are plotted south of Miracle Hill because of groundwater conditions described in Table 2 and figure 13. The wells north of the fault are shallower than those south of it, and produce hotter water—generally above 90° F. The extension of the Miracle Hill fault is based on the marked alignment of groundwater contours

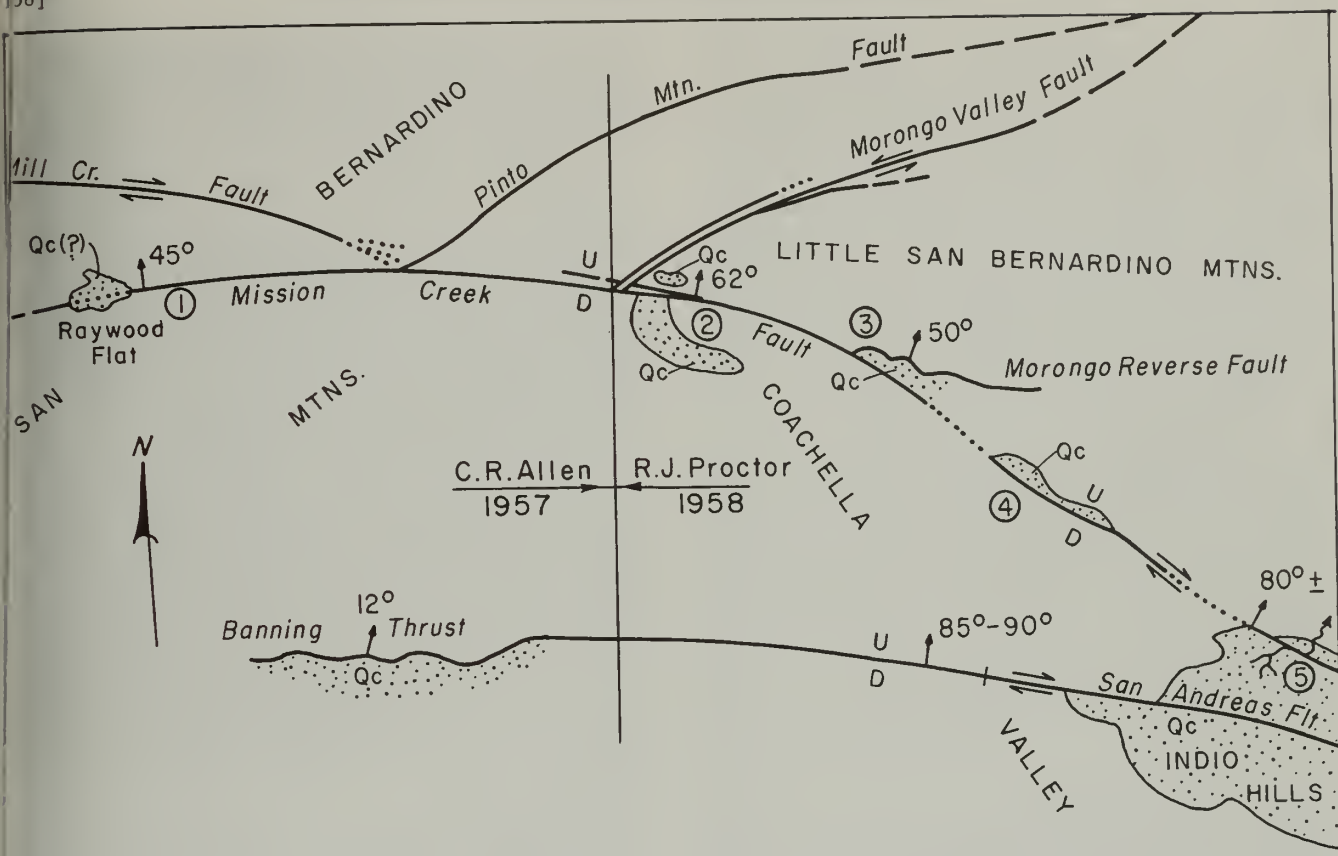


Figure 9. Sketch showing relative movements of Mission Creek fault in Recent time based on disturbance of late Pleistocene conglomerate (Qc) and Recent alluvium. See text for discussion. ① no displacement since Pleistocene. ② 1100 feet vertical, Recent. ③ 500 feet vertical, Recent. ④ 110 feet vertical, very recent. ⑤ 800 feet horizontal, very recent.

through Desert Hot Springs, as shown on figure 13. Branch faults should probably be expected under the alluvium because many faults are exposed in the Mission Creek fault zone in older rocks to the northwest. These branch faults may or may not continue farther southeast under the alluvium.

(3) In the Indio Hills immediately off the geologic map, several streams flowing on late Pleistocene or early Recent conglomerate are offset a maximum of 800 feet in a right-lateral sense. Dibblee (1954, p. 26) describes right-lateral offset in the eastern Indio Hills. The regional tectonic evidence shows the dominant component of displacement is right lateral for most faults in the region.

Age. The Mission Creek fault is at least as old as late Miocene: Allen (1957, p. 342) finds upper Miocene (?), or older, Coachella basalt crushed and "evidently . . . extruded along the fault zone" west of the area of this report. If the fresh-looking diorite porphyry between Big Morongo and White House Canyons was intruded locally along the fault zone, rather than as a fault sliver, the Mission Creek fault existed in Early Cretaceous time.

The Desert Hot Springs earthquake of 1948.* A strong earthquake, of magnitude $6\frac{1}{2}$, was felt at 3:43 p.m., December 4, 1948; its epicenter was in the foot-

hills of the Little San Bernardino Mountains $1\frac{1}{2}$ miles east of the mapped area, in East Wide Canyon, directly below the Colorado River Aqueduct. No scarp or other surface evidence of the quake was found the following day, except local talus-slides.

This earthquake has been exceeded in magnitude by only three others in southern California within the past 50 years; it would certainly have caused considerable damage had it occurred in a metropolitan area, rather than a sparsely settled region of the desert. Aftershocks continued for at least 10 years.

Within 8 hours after the main shock, three portable seismographs were operating within an 8-mile radius of the epicenter, enabling the aftershocks to be plotted with unusual accuracy.

The 72 aftershock epicenters "are concentrated in a zone 18 km long, parallel to the Mission Creek fault trace . . . but 5 km north of it. Aftershock activity is markedly concentrated toward the two ends of this line. Location of the main shock suggests that fracturing started near the southeast end and progressed northward" (p. 315). The westernmost epicenter was about 1 mile west of Long Canyon. "Although this offset might be used as an argument against the association of these earthquakes with the Mission Creek fault, a more reasonable hypothesis is that the fault plane dips north and thus effectively displaced the epicenters from the surface trace. Assuming a hypo-

* Data mainly from Richter, Allen, and Nordquist, 1958.

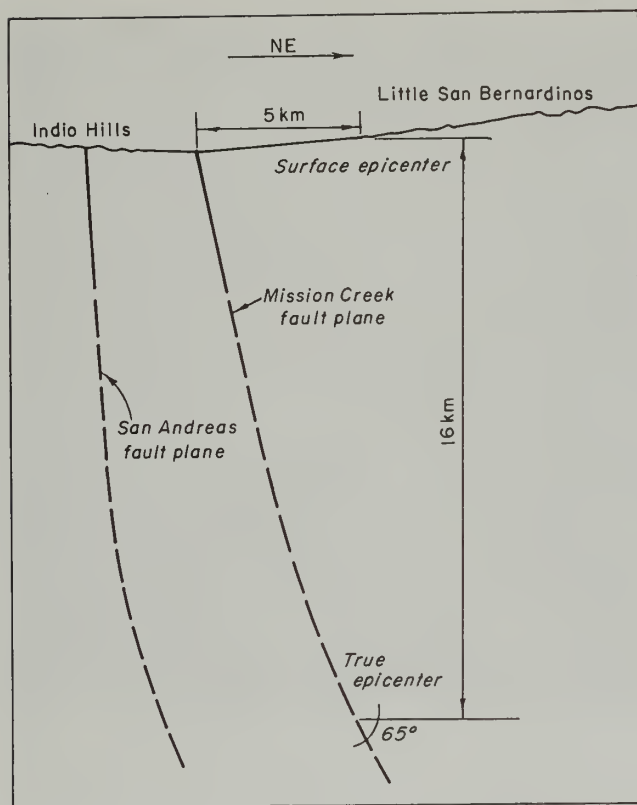


Figure 10. Projected dip of Mission Creek fault plane based on evidence of movement of Desert Hot Springs earthquake of 12/4/48. Earthquake data from Richter, Allen, and Nordquist (1958).

central depth of 16 km, the 5 km offset would indicate a gentle curve with an average dip of 73° for the fault plane" (p. 330). (See figure 10.)

Various seismological observations "... demand that the dip of the fault plane [at the earthquake focus] be at least as shallow as 65° , which is consistent with other field and seismic data" and "... an oblique displacement, which must be a combination of thrust-slip and right lateral-slip" (p. 332). Thus the field evidence is borne out: the Mission Creek fault progresses from essentially low-angle reverse movement in the western part of the mapped area to essentially high-angle right-lateral movement in the east, with various degrees of combined movements in the Desert Hot Springs area.

Morongo Valley fault

The frayed northeast-trending fault on the south side of Morongo Valley is herein named the Morongo Valley fault. It is a zone of several branching faults: two abutting the Mission Creek fault at its southwestern terminus; three in southern Morongo Valley; and one major break—the middle branch—merging with the Pinto Mountain fault 6 miles northeast of the geologic map (see fig. 12).

Physiography. At the western terminus of the Morongo Valley fault, a wedge of Cabezón Fanglomerate lies in a narrow graben between two branches of the fault, whereas the mountains on both sides have risen. The boundaries of this graben consist of a thick-

ness of several feet of light-green gouge in gneiss of the San Geronio igneous-metamorphic complex. The mountains have risen uniformly on either side of this fault zone as indicated by their relatively flat plateau-like uplands.

Just east of the low hills near Twentynine Palm highway, the middle branch of the Morongo Valley fault can be traced a short distance on the alluvium and the southern branch makes a groove on a thin soil cover on the mountain slope east of the hills. At the northern edge of the geologic map, the fault cuts but does not displace fanglomerate. The intermittent trace of this fault can be observed for at least 6 miles northward of the mapped area, along the northern base of the Little San Bernardino Mountains.

Displacement. Morongo Valley is interpreted as a wedge-shaped graben bounded by faults on three sides—the south (Morongo Valley fault zone), west (Dry Morongo fault), and the north (of which there is no direct evidence except the mountain front itself). Two miles north of here the Pinto Mountain fault forms an escarpment which can be traced intermittently eastward for 50 miles (fig. 8). Apparent relative vertical displacement on the Pinto Mountain fault in Morongo and Yucca Valleys, northeast of the geologic map, supports the graben hypothesis for Morongo Valley. However, much more work remains to be done in this critical area.

Three lines of evidence indicate that the Morongo Valley fault is left lateral; it may be the only left-lateral fault in the area:

- (1) Parts of a hill at the southwestern end of Morongo Valley appear to be offset left laterally by the Morongo Valley fault and its branches;
- (2) Dry Morongo Creek appears to be left laterally offset along the fault in Morongo valley: Brown (in Thompson, 1929, p. 640) mentioned this "sharp bend of Dry Morongo Creek." (Of course, the stream may have preferred this course regardless of faulting, or even may have been a later development and followed the zone of weakness by headward erosion.)
- (3) The junction (etc.) of the Morongo Valley and Mission Creek faults closely resembles the junction of the left-lateral Garlock and right-lateral San Andreas faults 100 miles to the northwest; both junctions coincide with major changes in trend of the San Andreas fault zone. Hill and Dibblee (1953, p. 453) first made such a comparison with the "Warren's Well" (Pinto Mountain)—Mission Creek faults junction.

Morongo reverse fault

Beginning in Big Morongo Canyon (type locality) and ending in Little Morongo Canyon 3 miles eastward is the very conspicuous Morongo reverse fault. In the west it disappears under the unbroken Cabezón Fanglomerate on top of the ridge between Big Morongo and Dry Morongo Canyons. Here the fault plane's dip of 39° to the north is the shallowest recorded. As does the Mission Creek fault, the Morongo reverse fault dips progressively more steeply towards the east, first abruptly, then gradually; in Little Morongo Canyon, where the fault trace disappears, the dip is 68° to the north. The fault forms a conspicuous scarp between gneiss and sediments, with little or no crushing except for an indistinct crushed greenish zone within the gneiss. In White House Canyon, the gneiss forms a 40-foot high scarp overriding the Cabezón Fanglomerate.

The Morongo reverse fault undoubtedly is associated with the Mission Creek fault zone, and they prob-

bly join at its western terminus beneath the undisturbed Cabezon Fanglomerate. Although if true, this would mean that there has been no Recent movement in Big Morongo Canyon, a few hundred feet eastward the gneiss overlying Pleistocene rocks indicates 500 feet of post-Pliocene vertical displacement.

South Pass fault

The fault shown at the base of the San Jacinto Mountains in San Gorgonio Pass is a conjectural extension of the unnamed fault shown by Allen (1957, Pl. 1). It expresses the author's beliefs that (1) the pass is a graben-like structure, not an erosional feature, and (2) that the northern and eastern San Jacinto Mountain front is a result of normal Quaternary faulting which was assisted, in part, by older batholithic intrusion at depth (Fraser, 1931, p. 522).

The pass, relative to the adjacent mountains, has increased its net elevation by 2,500 feet, while the mountains rose above 10,000 feet. Farther south, where this same trough becomes the much wider Imperial Valley, the depression probably remained at, or has been depressed below, sea level since the beginning of the Imperial Sea—roughly 12 million years ago. The mountain ranges bounding the Imperial Valley were not elevated to such heights as those at San Gorgonio Pass, even though structural relief in both areas may be similar.

The relatively undisturbed metamorphic rocks of the San Jacinto Mountains may have been originally ruptured along some line, such as the South Pass fault, because of forceful injection of the batholith at moderate depth. However, the writer believes that the major uplift of the block probably occurred in Quaternary time, because of (1) the abruptness of the front of the block itself; (2) the absence of large fans around the base of the range; (3) the fresh-looking nature of the granitic rocks, suggesting relatively little exposure to weathering; and (4) lack of post-Mesozoic sediments on the Coachella Valley or the east pass sides of the San Jacinto block. Fraser (1931) delineates the east face of the mountains with the north-trending Palm Canyon fault and suggests (p. 521) that it continues under the alluvium toward Whitewater. The writer believes the South Pass fault is simply the northern cousin of the Palm Canyon fault.

Other faults

Blind Canyon fault. This fault is best exposed in the terrace gravels and older alluvial fan remnants, suggesting that it was mainly active in early Recent time (Photo 9). As seen in a trench excavated for the expansion of the Colorado River Aqueduct in 1957, it has a 22-inch gouge zone with a westerly dip of 70°, where it cuts gneiss buried by 30 feet of undisturbed alluvium. Relative movement could not be ascertained; it may continue southward and merge with the Mission Creek fault at depth.

Disrupted fault west of Blind Canyon. This is an inactive fault that shows up strongly on aerial photos, but field examination discloses only a narrow rift-like canyon cutting across ridges and gullies. No gouge, breccia, or slickensides were observed although a somewhat crushed rock rubble was found in the higher,

more northerly parts of the zone; the southern portion is widened by erosion, filled in by alluvium, and covered by undisturbed terrace gravels. Apparently it was once an important fault, which was disrupted and rendered inactive by Recent mountain uplift along other faults.

Long Canyon fault. A conjectural, buried, north-trending fault is shown in Long Canyon to explain the termination of the three faults seen north of the Aqueduct that cannot be traced across the canyon. The linearity of Long Canyon and the abrupt difference in relief along a relatively straight line farther south, are further indirect evidence for such a fault.

Folds

The sedimentary rocks in the Indio Hills have been tightly folded between branches of the San Andreas fault zone, reflecting north-south shortening. Twelve northwest-trending subparallel folds occur within 4 square miles. Deformation appears to have been most intense during pre-Ocotillo Pleistocene time: the underlying Pliocene rocks everywhere dip more steeply than the Ocotillo beds, and in the northern Indio Hills, where it is much less deformed than in the south, the Ocotillo Conglomerate overlaps the Canebrake and Palm Spring Formations with an angular discordance of as much as 80°.

Whitewater Hill is a domical anticline or parma resulting from Recent warping. The undulate Cabezon surface, plus the superimposition of a radial drainage pattern on the terrace gravels on Whitewater Hill indicate that deformation is still continuing.

GEOMORPHOLOGY

The upper part of the Coachella Valley is rimmed by three mountain ranges, which form a crescent-shaped borderland opening southeastward to the Salton trough. These mountains have effectively walled in the northern desert except for the prominent gap occupied by San Gorgonio Pass. On the northeast are the Little San Bernardino Mountains, a thoroughly stream-dissected range, their core laid bare as a rugged Precambrian (?) terrain. The crest of the range is rather uniform, but tilted on a grand scale so that the summit, which is about 3,000 feet elevation in the mapped area, gradually steepens to a somewhat uniform elevation of over 5,000 feet in the area north of Indio, some 30 miles southeast. The flat upland plateau in the westernmost Little San Bernardino Mountains is a result of uniform uplift of the mountains between the Mission Creek and Morongo Valley faults.

At the western edge of the area, the foothills of the San Bernardino Mountains consist mainly of dissected old alluvial fanglomerates of four ages, dating from Miocene to Recent. Recent intermittent streams are eroding the walls of the uplifted older fans and re-depositing the debris onto the valley floor to form a gently sloping piedmont. Farther west the conspicuous San Gorgonio Peak (elevation 11,502 feet) looms above the horizon.

On the southwest are the bold, jagged, 10,000-foot San Jacinto Mountains, of which only a few spurs jut into the mapped area. It appears that the north face

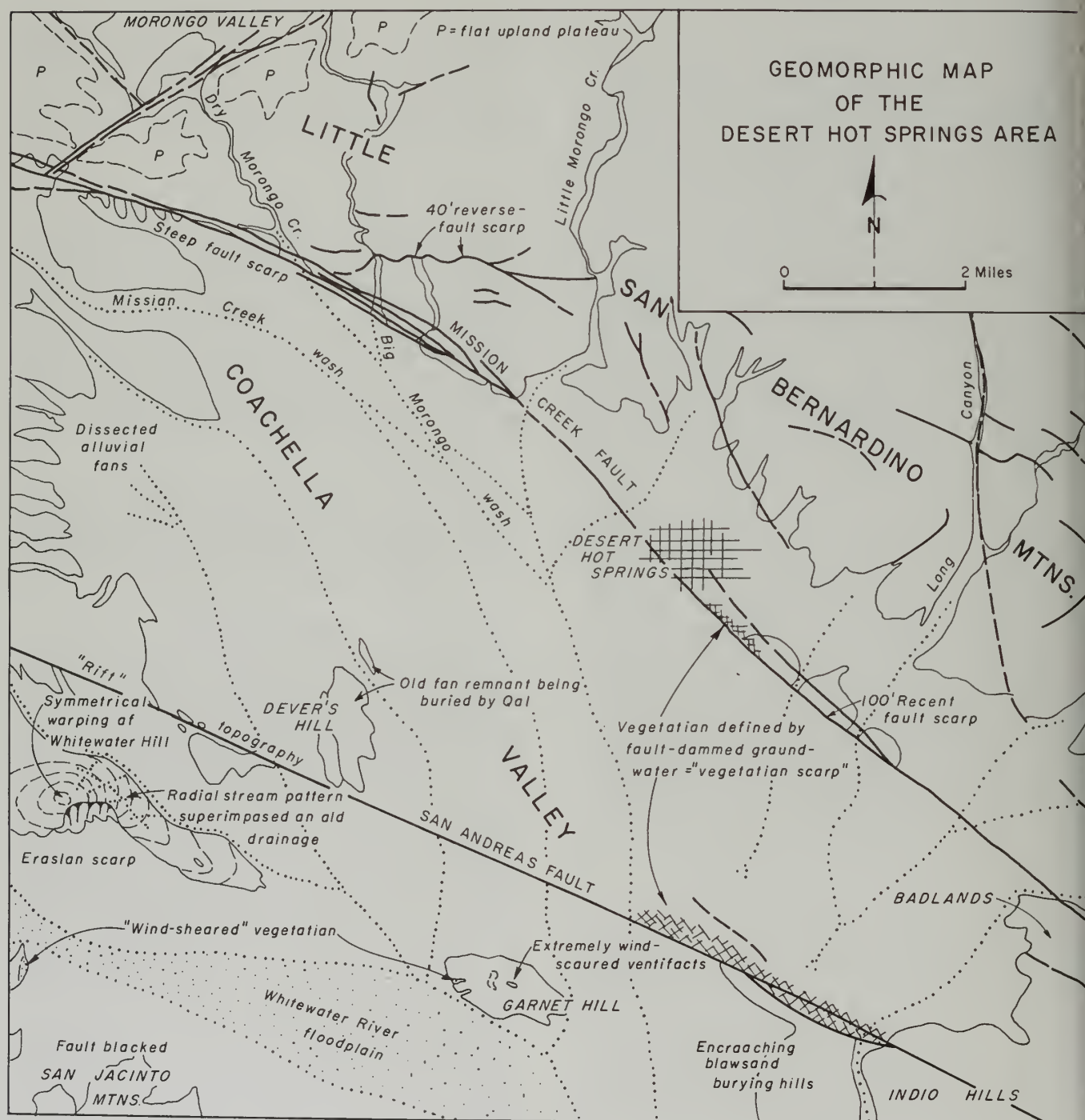


Figure 11.

f this mountain block has risen so fast that erosion has not had time to build up appreciable talus deposits on the slopes, nor alluvial fans at its base. The change in angle from mountain front to desert floor is probably as abrupt here as can be found anywhere in California; near Palm Springs the front rises 4,000 feet in a mile.

Extending southeast from the map area are the Indio Hills—a badlands 20 miles long and three miles wide, uplifted along the San Andreas fault zone. They are completely surrounded, and locally engulfed, by sand and alluvium. The western part is being buried by encroaching blowsand; the northern part is being buried by the alluvial fan piedmont of the Little San Bernardino Mountains; and the southern face, showing a sharp line marked by the San Andreas fault, is eroding away and building up its own small fan piedmont. The highest of the Indio Hills, in the western part, stand out 1,200 feet above the valley floor to the south, but only some 600 feet above the alluvium to the north. In the westernmost Indio Hills, at the south edge of the geologic map, the smooth-contoured outline of one large hill that is covered with wind-blown sand contrasts sharply with the gouged badlands to the east (Glendinning, 1949, p. 225).

Within the desert area shown on the geologic map several “islands”, or inliers, jut through alluvium. Dever’s Hill, near the center of the map, is a dissected mound of Cabezon Fonglomerate which is an inlier of the eroded old alluvial fans which form the foothills 2 miles west. Recent aggradation is slowly burying this old fan remnant. The absence from Dever’s Hill of the orange terrace mantle that is conspicuous on the low hills to the west and on the long tongue extending eastward from Whitewater Hill, is believed to be due to erosion; the contour lines on Dever’s Hill are a bit less regular than on the low mound immediately west, or on Whitewater Hill, 3 miles southwest.

Garnet Hill, a low anticline faulted up by the now-buried Garnet Hill fault, is believed to be a much older hill than either Whitewater Hill or Dever’s Hill, from three lines of evidence: (1) The fanglomerate on Garnet Hill was deposited upon an eroded surface of lower Pliocene Imperial Formation. (2) The mantle of fanglomerate on Garnet Hill is considerably thinner than on Whitewater Hill or the Indio Hills (compare sections A-A’ and E-E’ with F-F’), suggesting that Garnet Hill already existed as a low mound when the fanglomerate was being deposited. (3) Garnet Hill is much more intricately eroded than any other hill in the upper Coachella Valley, even though the rocks are of the same type and durability on Whitewater Hill, Dever’s Hill, and the Indio Hills. Boulders polished and grooved by sandblasting, and smaller curiously shaped ventifacts are common on Garnet Hill and Windy Point (Photo 10) but are scarce elsewhere.

Drainage

All streams in the mapped area are intermittent or ephemeral, flowing only after a localized summer thundershower or, more commonly, during a strong winter cyclonic storm. The entire mapped area is ultimately drained by the Whitewater River, which has a 1,200 square mile watershed, into Salton Sea.



Photo 10. The windward side of a diorite boulder atop the ridge of Windy Point. Note the deep intricate grooves sculptured by sand-laden wind. Where quartz grains are present, upon close inspection, they stand out sharply above the softer feldspars.

Dry Morongo, Big Morongo, and Little Morongo Creeks flow across the 2-mile width rather than down the 7-mile length of Morongo Valley, and then cut directly through the Little San Bernardino Mountains. This presents an interesting geomorphic problem: were the streams antecedent to uplift, or did headward erosion—cutting south from Morongo Valley and north from Coachella Valley—entrench them through the range? The answer is probably a combination of the two. The major uplift (probably in late Pleistocene time) could not have been more rapid than the rate at which the creeks were cutting their canyons, or a lake would have formed in Morongo Valley which would have overflowed the low divide at its southwest end.

There is no evidence for an ancestral stream draining Morongo Valley to the southwest. Headward erosion of the southwest end of Morongo Valley, from either south or north, cannot be considered important, at least at present, owing to the scant 4-inch annual rainfall in that area. The volume of water needed to excavate Dry Morongo, Big Morongo, and Little Morongo Creeks was probably supplied from the northwest during Pleistocene time, when glacier-producing climates¹ caused torrential runoff from the east slopes of the San Bernardino Mountains (fig. 8). The

¹ The southwesternmost glaciers in the United States were on San Geronio Peak (Sharp, Allen, Meier, 1959).

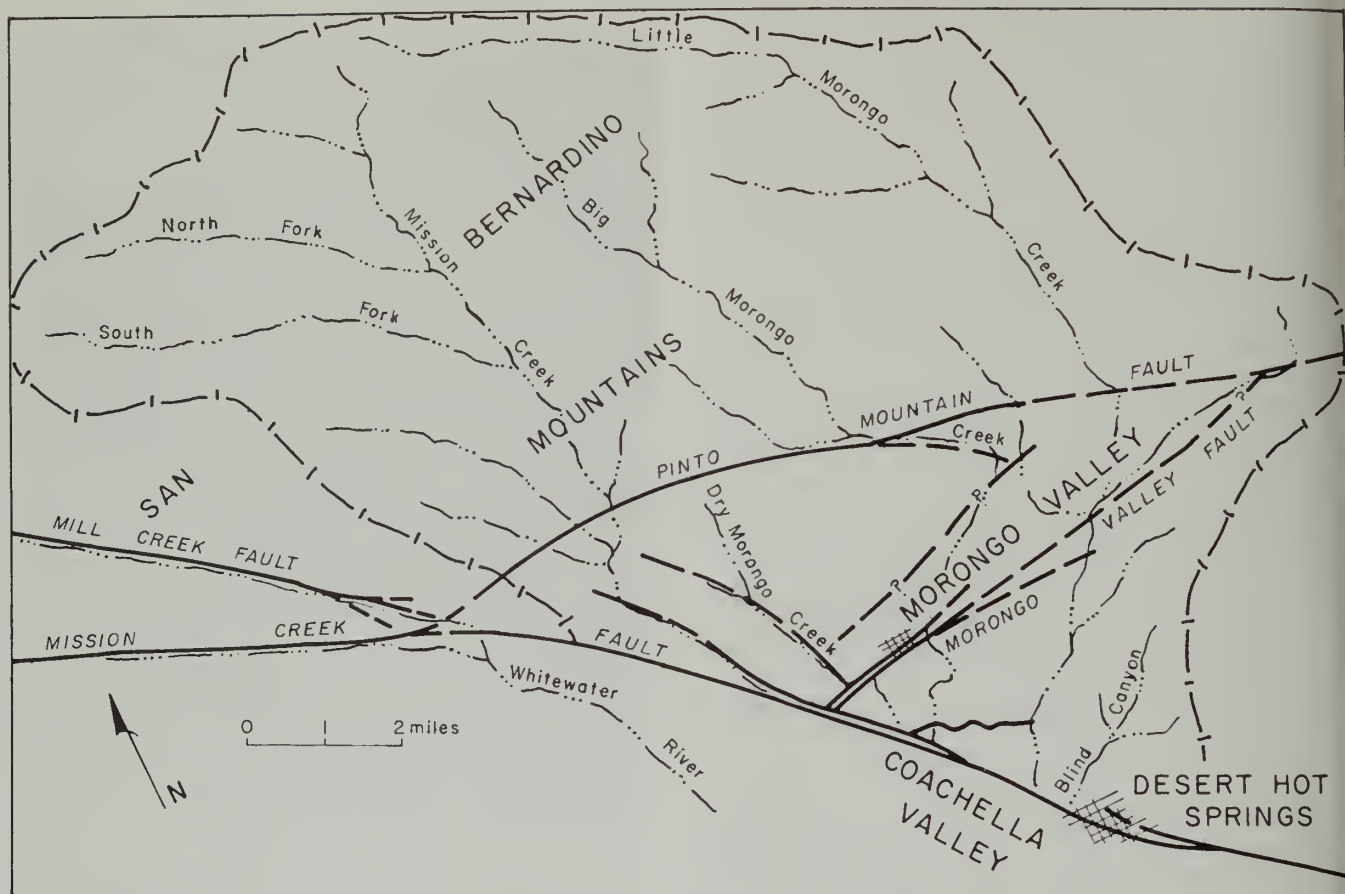


Figure 12. Watershed of Mission, Dry Marango, Big Morongo, and Little Morongo Creeks. Major source for Upper Coachella Valley and Desert Hot Springs ground water supply.

quantity of runoff could have been no greater than that required to degrade less than 1 inch each century, and still account for the present depth of cutting through the range. Although deformation of terrace deposits would be hard to prove, remnants of an old stream course are perched at least 100 feet above the present stream bed in Little Morongo Canyon. For all these reasons, antecedency appears to be a better answer than headward erosion to the problem of what controlled Morongo Valley drainage. This is in contrast to Vaughan (1922, p. 334), who believed Dry, Big, and Little Morongo Creeks captured an ancestral east-flowing Morongo Valley stream.

GEOLOGIC HISTORY

The geologic record is incomplete in this region owing largely to the lack of fossils except in the lower Pliocene marine Imperial Formation, and the lower Pleistocene horse and camel bones found in the Palm Spring Formation in the Indio Hills. Abundant indirect geologic evidence, however, gives a rather complete picture of the past with all hiatuses representing periods of non-deposition. The principal events are described in outline form below:

1. **PRECAMBRIAN (?)**—San Geronio (Chuckwalla) gneiss derived from sediments deposited by ancient sea.

Later burial and still later dynamothermal metamorphism with injection of granitic rocks at depth; localized secondary granitization and regional metamorphism.

2. **LATE PALEOZOIC**—Marine deposition of limestone and other sediments to the south, which were later buried and dynamothermally metamorphosed to form the metamorphic rocks of the San Jacinto Mountains. (The San Jacinto and San Geronio metamorphic terrains may have been juxtaposed by considerable strike-slip movements).

3. **CRETACEOUS**—Two periods of injection of granitic stocks, dikes, sills, pegmatite, and discordant stringers into the gneisses.

4. **LATE MIOCENE (?)**—Coachella Fanlomerate deposited as San Bernardino Mountains start to rise.

5. **EARLY PLIOCENE**—Inursion of ancient Gulf of California sea; deposition of at least 1,660 feet of marine Imperial Formation upon rocky coastline of San Geronio gneiss and Coachella Fanlomerate (and/or Split Mountain Formation in the Indio Hills and southward).

6. **MIDDLE PLIOCENE TO EARLY PLEISTOCENE**—Continental Canebrake Conglomerate/Painted Hill Formation, and Palm Spring Formation deposited conformably upon Imperial beds.

Tilting of sediments as San Bernardino Mountains continue to rise.

7. **LATE PLEISTOCENE**—Folding in Indio Hills.

San Jacinto and Little San Bernardino Mountains begin to rise.

Cabezan Fanlomerate/Ocotillo Conglomerate deposited unconformably on all older rocks except metamorphic rocks of the San Jacinto Mountains.

8. **RECENT**—Folding continues.

Terraces deposited (Old alluvium surface).

Continued uplift of mountains with erosion dissecting all older rocks.

Warping and uplift of Whitewater Hill.

Area ultimately drained by Whitewater River to Salton Sea.

Alluvium presently being deposited on valley floor; superficial wind-blown sand being deposited.

Faulting continues to be active.

ECONOMIC GEOLOGY
Petroleum

Of eight wells drilled in the mapped area, all except Edom" and More No. 1, were spudded prior to 1927. The well data are incomplete owing to poor records kept by these early companies. The data for "Edom" and More No. 1 were obtained by the writer; the older records were compiled by Jennings and Hart (1956, p. 63). All wells were dry holes.

The only reliable core data are those for the "Edom" well, furnished by The Texas Company; they are shown in structure section E-E'.

		Name of company and well	Date drilled	Total depth (feet)
T. R.	Sec.			
S	3E	25 Painted Hills Oil Assn.; No. 1	1920-25	1,400
S	4E	11 Amundson, Floyd; No. 1	1926	212
S	4E	14 Century Oil Assn.; No. 1	1921-24?	500
S	4E	30 Painted Hills Oil Assn.; No. 2	1921-24?	400
S	4E	33 Wallenberg; Daisy 1	1918-?	?
S	4E	4 Banning Oil Co.; No. 1	1921-30	975
S	3E	1 C & K Oil Co.; More No. 1	1957	?
S	5E	35 The Texas Co.; "Edom" Stone 1	1954	7,468

Because of the negative results of the wells drilled in this area (and others in the Imperial Valley), plus the fact that the marine Imperial Formation cannot be highly regarded as an oil bearing formation owing to its near-shore origin and unfavorable lithology, it is the opinion of the writer that there is little possibility of finding oil in commercial quantities in this region, unless a yet unknown pre-Miocene marine formation should be found at great depth.

Mines and quarries

Sand and gravel for aggregate, and decorative stone are the only mineral commodities being produced from the mapped area in 1960; copper and gold showings have been explored in the past. Relatively pure limestone is present but has not been developed on a large scale.

At the western edge of the geologic map, and extending half a mile west, a decorative building stone called "Whitewater stone" is obtained from two quarries. Whitewater stone, a hydrothermally altered gneiss and schist, is used for building facings, patios, walls, fireplaces, and other masonry throughout southern California. The quarry shown on the geologic map (Super Creek mine—now Starlight quarry) contains red hematite-stained mica schist with occasional thin, 5 mm long porphyroblasts of black tourmaline. It is owned by B. Opperman of Desert Hot Springs. The other property, the Painted Hill Quarry, contains varicolored yellow and red mica schist, with mica slightly less abundant; white and lavender shades are present but not common. It is owned by Miss K. McKenzie of Whitewater. The wholesale price of Whitewater stone varied between 23 and 28 dollars per ton in Los Angeles in 1960.

Two small occurrences of copper minerals were staked out in West Blind Canyon in 1954. One is the

Cactus Hill mine, a 20-foot adit; the other, a mile southwest, is called the Indian Copper mine, a 50-foot vertical shaft. Both mines were inactive in 1960. The Cactus mine tailings showed dark brown sphalerite, galena, and a trace of scheelite under ultraviolet light. Possible ore minerals include chalcocite, chalcopyrite, malachite, and azurite. The many contact metamorphic minerals at the Cactus Hill mine were mentioned under the heading Xenolith breccia.

Local residents report that a vein-quartz gold mine called the Hager-Kale mine was worked prior to 1911 in sec. 2, T. 3 S., R. 5 E. The mine was not located in the field, but an approximate location is shown about one mile east of the mouth of Long Canyon.

Many of the recrystallized limestone beds near Windy Point are relatively pure calcite and are of potential economic importance. However, strong opposition has been expressed by the people of Palm Springs and vicinity against the establishment of a cement plant, because of fears that such a plant might cause smoke and dust. At least one potential operator abandoned a proposal to establish a cement plant, the announced reason being opposition from residential property owners. A lens of white limestone in West Blind Canyon, 2 miles north of Desert Hot Springs, has been quarried recently for local use as roofing granules.

Aggregate

Two sand and gravel plants were operating in the area in 1961. The largest is the Massey Company plant just south of Garnet. An idle plant is located at the town of Whitewater (see Pl. 3). Desert Hot Springs Ready Mix operates a crushing, screening, and batch plant in Little Morongo Canyon; the town of Desert Hot Springs is practically the sole consumer of their aggregate, mainly in house and motel foundations, curbs, and sidewalks.

From June 1957 to February 1958, the Gunther-Shirley-Lane Company (subcontractors for American Pipe and Construction Company) supplied aggregate for concrete used in precast pipe and other appurtenances for the Metropolitan Water District's aqueduct expansion in this area. This huge portable plant was located southeast of the junction of Twentynine Palms highway and the aqueduct conduit. Dry Morongo Wash was the source for the aggregate.

Mineral Water

The main reason for the present existence of the town of Desert Hot Springs is the occurrence of naturally hot mineral water in a very localized area, structurally controlled by faults.

According to Mr. William Tarbutton, who has drilled more than 100 wells in this area, the thermal waters occur in three known water-bearing strata or aquifers. These aquifers slope from the Mission Creek fault downward toward the mountains to the north, so that the depths to the upper aquifer vary considerably. The gap between the first and second aquifer, where present, is about 80 feet, and between the second and third about 30 feet. The lowermost is generally the most prolific aquifer, and yields the hottest water in almost all wells. The Lucky 7 well in Table 2

is a good example. In some wells one or two of these strata may not be definitely recognized during drilling.

The rocks encountered in drilling are variously described in such driller's terms as sandy loam, silty sand, and bouldery sand. Inasmuch as the alluvium, Cabezon/Ocotillo, and Canebrake rocks are all similar fan-glomerate types, and all occur in the section in the Desert Hot Springs area, it is almost impossible to ascertain from well data which formation contains the three aquifers.

The water temperature in the 51 wells in Table 2 ranges from 77° F. to 200° F., but average about 122° F. The depth to water ranges from 16 feet to 340 feet, the latter obtained from sheared or jointed gneiss; at a natural spring at Miracle Hill the water level rises to the surface along the Miracle Hill fault, a north branch of the Mission Creek fault. Holmes well, with total depth of 270 feet, is the deepest water-producing well north of the Miracle Hill fault. South of the fault, the static water level averages about 100 feet deeper than in wells only a few hundred feet away, north of the fault. Towards the San Andreas fault, the water table also rises nearer the surface, and forms a spring at Seven Palms Ranch. The only artesian wells in the upper Coachella Valley occurred in the vicinity of this spring.

The amount of fluoride concentration in water for human consumption is critical; the California Department of Public Health inspects all wells periodically, and requires that fluoride be kept under 1.2 ppm. Wells within this area generally contain less than 1 ppm fluoride, but some contain as much as 8.40 ppm fluoride. Therefore, the water from certain wells of the Desert Hot Springs County Water District must be mixed to meet the fluoride requirement.

The analyses shown in Table 1 were obtained from several sources. "Typical" refers to samples from several wells in the town of Desert Hot Springs but definite locations, depths, and name of the analysts were unavailable. Water from well #1 was analyzed by Edward S. Babcock and Sons, Riverside, and is probably the most reliable.

By comparing the data of Tables 1 and 2 for wells of the Desert Hot Springs area with similar data from the comprehensive study of the lower Coachella Valley by Huberty, Pillsbury, and Sokoloff (1948), some generalizations can be stated about the differences in quality of ground water between these areas. From the upper to the lower Coachella Valley, (1) percentage of sodium (total cations) increases, while calcium plus magnesium ions decreases; (2) electrical conductivity decreases from an average of 325 in the upper, compared to 1061 in the lower part of the valley; (3) temperature of water consistently decreases towards the lower Coachella Valley, ranging from 119° to 67° F.; (4) alkalinity increases: of the 120 wells Huberty, et al., studied, 22 were over 8.5 pH, and only two as low as the 7.4 pH for well #1 in Desert Hot Springs. Furthermore, wells in the northern part and around the rim of the valley generally have to be pumped, whereas most of the wells in the lower central Coachella Valley are artesian.

Table 2 and figure 13 are compilations of data from 54 wells, obtained from Riverside County Health De-

partment, Desert Hot Springs County Water District, Albert A. Webb Associates, Civil Engineers, and Mr. Tarbutton. The depths to water and temperatures are given for the upper aquifer. All wells are located in T. 2 and 3 S., R. 5 E., S.B.M., with the exceptions of wells Cree and Herbold which are in T. 2 S., R. 4 E. (see fig. 13).

As seen in figure 13, correlation between depth to top of the upper aquifer and temperature is not sharp. However, in a general sense, the Mission Creek fault zone is an abrupt barrier both to ground water depths and to temperature variations on either side of the zone.

Table 1. Analyses of Desert Hot Springs Water.

(Data in parts per million, except Na.)

	"Typical"	Well #1 ¹	Holmes ²
<i>Cations</i>			
Silica (SiO ₂)-----	20.7	--	47
Magnesium (Mg)-----	4.9	2.9	1
Calcium (Ca)-----	21.6	94.0	54
Sodium (Na)-----	23.9%	42.3%	83.8%
Potassium (K)-----	--	0.00	--
<i>Anions</i>			
Carbonate (CO ₃)-----	4.5	0	12
Bicarbonate (HCO ₃)--	39.6	15.1	15
Sulfate (SO ₄) ³ -----	392.6	386	548
Nitrate (NO ₃)-----	--	0.00	--
Chloride (Cl)-----	102.0	60	185
Fluoride (F)-----	4.6	0.8	6.9
<i>Hardness</i>			
Calcium carbonate (CaCO ₃)-----	--	69.0	--
Boron (B)-----	--	0.00	--
Iron and aluminum (Fe, Al)-----	Trace	27.0	Trace
Total dissolved solids: 824		770	--

Hydrogen ion activity (pH) = 7.4 (well #1)

Specific conductance (K × 10⁶) at 25° Centigrade = 1182 micromhos (well #1).

¹ Sample taken from 92-foot depth at a temperature of 88° F.

² Sample taken from 270-foot depth at a temperature of 170° F.

³ Sulfate content generally increases with depth of well.

Because the rainfall in the mapped area is inadequate to maintain the high water table, another source area must be considered. The east flank of the San Bernardino Mountains, 8,000 feet high, is the origin of the surface runoff for Big Morongo, Little Morongo, and to a lesser extent, Dry Morongo Creeks, and is believed to be the source of recharge for the ground water basins in the Desert Hot Springs vicinity. The streams flow, mainly underground, through the porous alluvium of Morongo Valley and the Little San Bernardino Mountains. The ground water in the alluvium is then dammed by the gouge-filled Mission Creek fault zone, creating an underground reservoir. Because the eastern San Bernardino Mountains are mainly a wilderness area, there is little contamination by microscopic organisms; the only bacteriological counts made by the Riverside County Health Department are of *Escherichia coli*.

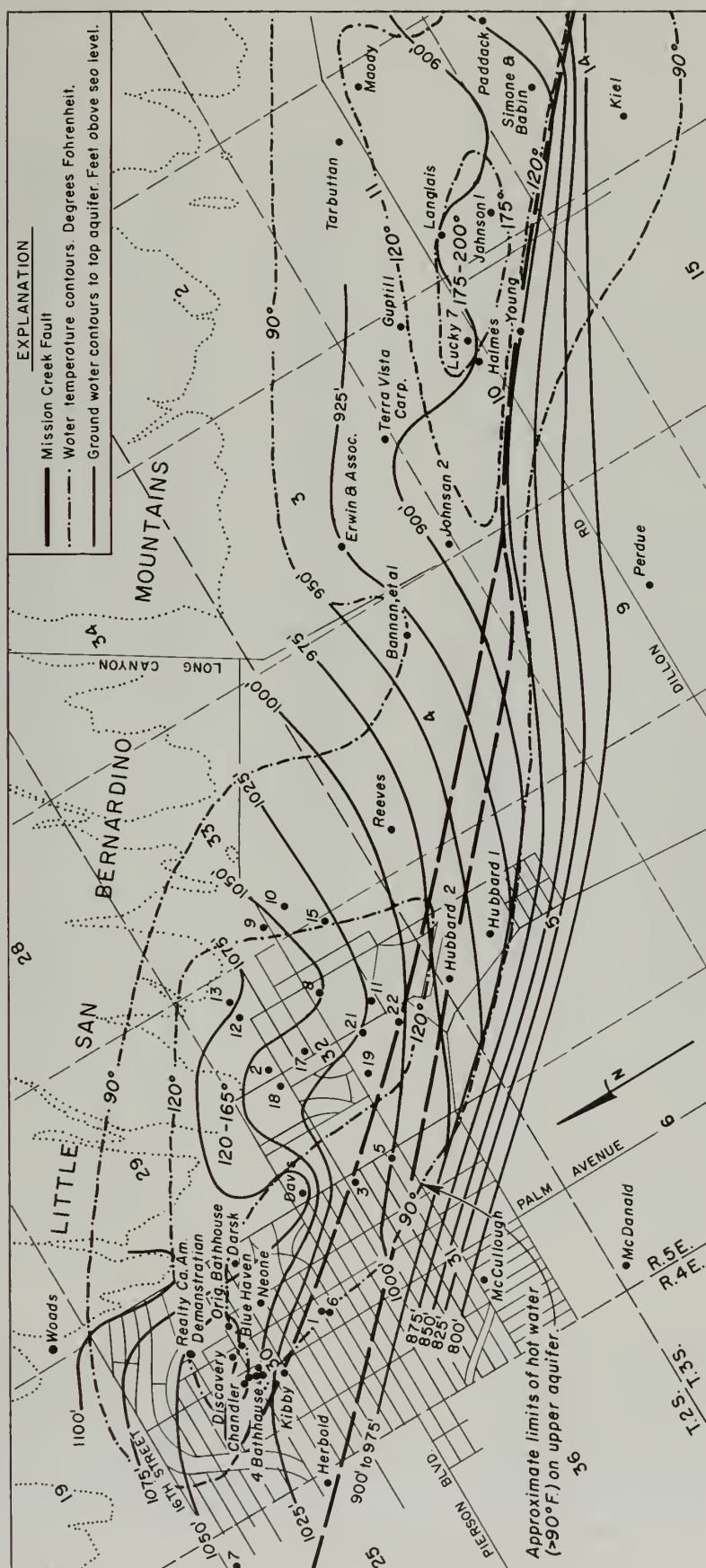


Figure 13. Water wells in the Desert Hat Springs area.

Table 2. Water Well Data.
(Depth and temperature readings on upper aquifer)

Name of well	Location	Date drilled	Depth to water (feet)	Temperature °F.	Ground elevation (feet)
Discovery.....	sec. 30	1934	154	146	1200
Original Bath House.....	"	pre-1940	170	118	1210
Coffee Bath House Wells (4).....	"	1940-1954	157	108-116	1195
Chandler.....	"	pre-1950	160	125	1210
Blue Haven.....	"	pre-1950	140	130	1200
Realty Co. of America Demonstration.....	"	1952	212	120	1260
Dorsk.....	"	1957	149	120	1240
Kibby.....	"	1951	135	77	1160
Neone.....	"	1946	127	104	1180
#1 (Desert Hot Springs Co. Water District).....	"	1941	92	88	1096
#6 (Desert Hot Springs Co. Water District).....	"	1955	90	88	1098
#7 (Cree; Desert Hot Springs Co. Water District).....	sec. 25	1950 & 1957	161	82	1195
Herbold.....	"	1947	132	82	1150
Woods.....	sec. 20	1939	340 ¹	80	1450
#2 (Miracle).....	sec. 32	1948	143	145	1190
#8.....	"	1952?	76	142	1135
#11.....	"	1956	40	146	1065
#12.....	"	1952?	150	134	1220
#13.....	"	1952?	165	153	1240
#15 (Yerxa #1).....	"	1940	90	122	1115
Davis.....	"	1949	128	102	1125
#17 (Templeman).....	"	1955	95	156	1135
#18 (Angel View Crippled Childrens Foundation, Inc.).....	"	1955	138	136	1170
#19 (Schwartz).....	"	1955	54	150	1070
#21 (Yerxa #3).....	"	1940	40	140 ²	1065
#22 (Sullivan).....	"	1956	161 ³	166	1010
McCollough.....	sec. 31	1940 & 1954	220	88	990
#3 (Desert Hot Springs Co. Water District).....	"	1940	48	95	1060
#5 (Desert Hot Springs Co. Water District).....	"	1948	29 ⁴	95	1030
#9 (Highland's Desert Hot Springs).....	sec. 33	1955	165	120	1215
#10 (Simone and Babin).....	"	1954	136	112	1185
Hubbard #1.....	sec. 5	1946	16	108	960
Hubbard #2 (Bubbling Wells).....	"	1947	23	108	990
McDonald.....	sec. 6	1957	190	82	960
Reeves.....	sec. 4	1949	76	95	1070
Bannon, et al.....	"	1957	182	90	1115
Perdue.....	sec. 9	1947	168	80	940
Erwin and Assoc.....	sec. 3	1954	225	98	1150
Terra Vista Corporation.....	"	1954	164	94	1060
Johnson #2.....	"	1955	147	106	1045
Holmes.....	sec. 10	1951	80	165	980
Lucky 7.....	"	1950	83	184 ⁵	990
Young.....	"	1951	75	118	945
Guptill.....	"	1956	117	106	1030
Langois.....	sec. 11	1953	110	175	1010
Johnson #1.....	"	1951	105	175	1000
Moody.....	"	1956	170	150	1090
Tarbutton.....	"	1955	112	96 ⁶	1025
Kiel.....	sec. 14	1951	265	103	990
Simone and Babin.....	"	1953	148	130	1040
Paddock.....	"	1956	220	134	1090

¹ Water in sheared or jointed gneiss. Total depth of well is 487 feet.

² Temperature is 176° F. at 200-foot depth.

³ Middle water strata; spring at surface nearby is the only surface water occurrence in the area.

⁴ Total depth is 807 feet, deepest well in area.

⁵ Hottest water well in region. Middle aquifer at 157-167 feet yields 188° F.; lower aquifer at 188-218 feet yields 200° F.; total depth of well is 331 feet but no water beyond 218 feet.

⁶ Temperature at 210-foot depth is 125° F.

Summary of conclusions: (1) Runoff from the east flank of the San Bernardino Mountains charges the Desert Hot Springs ground water basin, mainly by subsurface drainage. (2) The Mission Creek fault zone effectively dams the gravitational flow of a large share of the ground water flowing down the Coachella Valley, and raises the water table near the surface in the area north of the fault. (3) The water becomes min-

eralized and is heated at depth, probably by emanating gases and hydrothermal activity associated with the fault zone; radioactivity is not believed to be a source of heat because no abnormal radioactivity has been detected in ground water in this area. (4) The ground water then migrates laterally, principally into three permeable strata.

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SELECTED BIBLIOGRAPHY OF THE COACHELLA VALLEY, SALTON SEA, AND VICINITY *

Compiled by Richard J. Proctor

*This bibliography ** includes publications selected from those that concern the several branches of earth science and related fields in the Coachella Valley and Salton Sea regions. Its purpose is to provide a ready reference to works on this area additional to those cited in the preceding text.*

References appear under the headings (1) Economic geology and mineralogy, (2) General references, (3) Geography, (4) Geology, (5) Hydrology, (6) Paleontology, (7) Salton Sea and tinct Lake Cahuilla, and (8) Soils.

Under General references are those treating the historic development of these regions; guidebooks; anthropology of the Cahuilla Indians; and references which cover a much larger area, but include a chapter or description of some aspect of the Coachella Valley, Salton Sea, or the surrounding mountains.

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